CHAPTER 8

CULVERTS

Chapter 8 Culverts
Table Of Contents

Chapter 8 Culverts
Table Of Contents

Appendices

8.1 Introduction

8.1.1 Purpose

This chapter provides general design procedures for the hydraulic design of highway culverts. For more in-depth discussion of the hydraulics of culverts see the FHWA Hydraulic Design Series Number 5 (HDS 5), Hydraulic Design of Highway Culverts. This chapter also presents results of culvert analysis using microcomputers that demonstrates the use of the HY8 culvert analysis software.

Culverts are structures designed to convey water through embankments, the hydraulics are for free surface flow approaching the culvert, with no consideration of the approach velocity (i.e. ponded conditions).

8.1.2 Definitions

Critical Depth

Critical depth is the depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry there is only one critical depth. Appendix D at the end of this chapter contains critical depth charts for different shapes.

Crown (Soffit)

The crown is the inside top of the culvert.

Flow Type

There are seven culvert flow types (USGS), but for highway culvert design a simplified approach with only two types of flow (inlet control and outlet control) are used. Diagrams of these flow types are provided in the design methods section.

Free Outlet

A free outlet has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

Headwater

Headwater is the depth of water that is be ponded at the upstream end of the culvert during the flood event.

Improved Inlet

An improved inlet has an entrance geometry which decreases the flow contraction at the inlet and thus increases the capacity of culverts. These inlets are referred to as either side- or slope-tapered (walls or bottom tapered).

8.1 Introduction (continued)

8.1.2 Definitions (continued)

Invert

The invert is the flowline of the culvert (inside bottom).

Normal Depth Flow

Normal depth flow occurs in a channel reach when the discharge, velocity and depth of flow do not change throughout the reach. The water surface and channel bottom will be parallel. This type of flow will exist in a culvert operating on a constant slope provided the culvert is sufficiently long so that normal depth is achieved.

Slope

- A steep slope occurs where normal depth is less than critical depth.
- A mild slope occurs where normal depth is greater than critical depth.
- Critical slope occurs where the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry there is only one critical slope.

Submerged

- A submerged outlet occurs when the tailwater elevation is higher than the crown of the culvert at the outlet end.
- A submerged inlet occurs when the headwater is greater than 1.2D where D is the culvert diameter or barrel height.

Tailwater

Tailwater is the depth of water that is at the downstream end of the culvert during the flood event.

8.1 Introduction (continued)

8.1.3 Symbols

To provide consistency within this chapter as well as throughout this manual the symbols given in Table 8-1 will be used. These symbols were selected because of their wide use in culvert publications.

Table 8-1 Symbols

Symbol	Definition	Units
A	Area of cross section of flow	Ft^2
AHW	Allowable High Water	Ft
B	Barrel width	Ft
D	Culvert diameter or barrel height	Ft. or in.
DHW	Design Highwater	Ft
d	Depth of flow	Ft
d_c	Critical depth of flow	Ft
g	Acceleration due to gravity	$Ft./sec^2$
H	Sum of $H_E + H_f + H_o$	Ft
H_b	Bend headloss	Ft
H_E	Entrance headloss	Ft
H_f	Friction headloss	Ft
H_L	Total energy losses	Ft
H_o	Outlet or exit headloss	Ft
H_v	Velocity head	Ft
h_o	Hydraulic grade line height above outlet invert	Ft
HW	Headwater depth (subscript indicates section)	Ft
K_E	Entrance loss coefficient	-
L	Length of culvert	Ft
n	Manning's roughness coefficient	-
P	Wetted perimeter	Ft
Q	Rate of discharge	Ft^3/sec
R	Hydraulic radius (A/P)	Ft
S	Slope of culvert	Ft/Ft
TW	Tailwater depth above invert of culvert	Ft
V	Mean velocity of flow with barrel full	Ft/sec
V_d	Mean velocity in downstream channel	Ft/sec
V_o	Mean velocity of flow at culvert outlet	Ft/sec
V_u	Mean velocity in upstream channel	Ft/sec
γ	Unit weight of water	Lb/Ft^3
τ	Tractive force	Lb/Ft^2

8.2 Design Goals & Guidelines

8.2.1 Design Goals

The following design goals are specific to culverts.

- All culverts that are to convey a quantifiable discharge (design flow) shall be hydraulically designed.
- The design flood selected shall be consistent with the class of highway and commensurate with the risk at the site.
- Culvert location in both plan and profile shall be investigated to avoid sediment build-up in culvert barrels.
- Culverts shall be designed with consideration of debris by either providing debris screens or by using an enlarged opening.
- Culverts in urban situations may need to have access barriers.
- Where practicable, some means shall be provided for personnel and equipment access to facilitate maintenance.

Length and Slope

The culvert length and slope shall be chosen to approximate existing topography, and to the degree practicable:
- the culvert invert shall be aligned with the channel bottom and the skew angle of the stream, and
- the culvert entrance shall match the geometry of the roadway embankment.

Debris Control

Debris control shall be considered:
- where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris,
- for culverts located in mountainous or steep regions,
- for culverts that are under high fills, and
- where clean out access is limited. However, access must be available to clean out the debris control device.

Screens are usually provided upstream of the culvert inlet, see Hydraulic Engineering Circular No. 9, "Debris-Control Structures" for design information.

Allowable Headwater

Allowable headwater is the depth of water that can be ponded at the upstream end of the culvert during the design flood that is limited by one or more of the following:

- non-damaging to upstream property,
- 3 inches below the edge of the pavements,
- equal to the elevation above which flow diverts around the culvert to another watercourse,
- May be limited to an elevation that does not adversely affect the performance of upstream culverts.

8.2 Design Goals & Guidelines (continued)

8.2.1 Design Goals (continued)

Tailwater Relationship - Channel

- Evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth for a range of discharges.
- Calculate backwater curves at sensitive locations or use a single cross section analysis. (Backwater curves yield the most accurate tailwater.)
- Use the critical depth and equivalent hydraulic grade line if the culvert outlet is operating with a free outfall.
- Use the headwater elevation of any nearby, downstream culvert if it is greater than the channel depth. A backwater surface profile may be appropriate if the tailwater significantly impacts the culvert under consideration.

Tailwater Relationship - Confluence or Large Water Body

- Use the high water elevation that has the same frequency as the design flood if events are known to occur concurrently (statistically dependent).
- If statistically independent, the tailwater should be evaluated for two conditions; 1.) that from the design peak flow of the culvert concurrent with the 10-year peak flow in the main watercourse, 2.) that from the 10-year peak flow in the culvert with the design peak flow in the main watercourse.

Maximum Velocity

At the design flow, the maximum velocity at the culvert exit shall be compared with the velocity in the natural channel as described in Section 612 2.C of the Roadway Design Guidelines (RDG).

- No protection is generally required in the natural stream if the outlet velocity is less than 1.5 times the natural stream velocity.
- Dumped rock riprap is generally sufficient for ratios between 1.5 and 2.0 with an outlet velocity less than 10 fps.
- Wire-tied rock riprap should generally be used where the ratio is 1.5 to 2.5 with an outlet velocity between 10 and 15 fps.
- Energy dissipators are required when the ratio between outlet and natural stream velocities is greater than 2.5 or the outlet velocity is greater than 15 fps.

Minimum Velocity

The minimum velocity in the culvert barrel shall result in a tractive force ($\tau = \gamma dS$) greater than critical τ of the transported streambed material at low flow rates.

- Use 2.5 ft/sec. when streambed material size is not known.
- If clogging is probable, consider installation of a sediment trap or size culvert to facilitate cleaning.

8.2 Design Goals & Guidelines (continued)

8.2.1 Design Goals (continued)

Flood Frequency

The flood frequency used to design the culvert shall be based on:

- the roadway classification, (Chapter 600, Roadway Design Guidelines)
- existence of FEMA mapped floodplains, and
- the level of risk associated with the 100-year event to adjacent property.

8.2.2 Design Features

Alternative Analysis

Culvert alternatives shall be selected that satisfy:

- topography (fit the site)
- design policies and criteria

Alternatives shall be analyzed for:

- hydraulic equivalency,
- environmental impact (changes in velocity, flow distribution, and alignment), and
- risk and cost.

The selected alternative should best integrate engineering, economic and social considerations. The chosen culvert shall meet the selected structural and hydraulic criteria and shall be based on:

- construction and maintenance costs,
- risk of failure or property damage,
- traffic safety,
- environmental or aesthetic considerations,
- social or nuisance considerations, and
- land use requirements.

Culvert Sizes and Shape

The culvert size and shape selected shall be based on engineering and economic criteria related to site conditions.

- The following minimum sizes shall be used to minimize maintenance problems and clogging: 24” pipe culvert, 6’x6’ box culvert, (a smaller box culvert may be used as required with approval of the Drainage Section Supervisor and District representative).
- Land use requirements, such as need for an equipment or animal pass, may dictate a larger or different barrel geometry than required for hydraulic considerations.
- Use arch or oval shapes only if required by hydraulic limitations, site characteristics, structural criteria, or environmental criteria.

8.2 Design Goals & Guidelines (continued)

8.2.2 Design Features (continued)

Multiple Barrels

Multiple barrel culverts shall fit within the natural dominant channel with minor widening of the channel so as to avoid conveyance loss through sediment deposition in some of the barrels. They are to be avoided where:

- the approach flow is high velocity, particularly if supercritical, (These sites require either a single barrel or special inlet treatment to avoid adverse hydraulic jump effects.)
- irrigation canals or ditches are present unless approved by the canal or ditch owner,

Culvert Skew

The culvert skew shall not exceed 45° as measured from a line perpendicular to the roadway centerline without the approval of the Drainage Engineer. Culvert skews shall be specified to no greater precision than 1 degree and should be constructible with standard designs of 15, 30, and 45 degrees skew.

Broken-back Culverts

Broken-back culverts may be necessary where the topography does not allow for a continuous grade. Broken-back culverts shall only be used with the approval of the Drainage Section.

End Treatment (Inlet or Outlet)

Inlet and Outlet end treatments are shown in the ADOT B- and C- standards. Culverts 48" and larger shall have a headwall. Culverts less than 48" shall have an end section.

Culvert ends may be protected from traffic impacts as follows:

- Small culverts, 30 in. in diameter or less, shall use an end section or slope paving.
- Culverts greater than 30-in. in diameter may receive one of the following:
    a. be extended to the appropriate "clear zone" distance as shown in the AASHTO Roadside Design Guide.
    b. safety treated with a grate if the consequences of clogging and causing a potential flooding hazard is less than the hazard of vehicles impacting an unprotected end. If a grate is used, the net area of the grate (excluding the bars) shall be 1.5 to 3.0 times the culvert entrance area.
    c. shielded with a traffic barrier if the culvert is very large, cannot be extended, has a channel that cannot be safely traversed by a vehicle, or has a significant flooding hazard with a grate.

Performance Curves

Performance curves may be used for evaluating the hydraulic capacity of a culvert. These curves will display the effects of different flow rates at the site and provide a basis for evaluating flood hazards.

8.2 Design Goals & Guidelines (continued)

8.2.2 Design Features (continued)

Outlet Protection

Outlet protection shall be provided where necessary due to excessive outlet velocities or a significant difference between the outlet velocity and the downstream channel velocity. See Energy Dissipator Chapter.

8.2.3 Design Methods

Hydrology Methods

A. Constant Discharge
- Is assumed for most culvert designs.
- Is usually the peak discharge.
- Will yield a conservatively sized structure where temporary storage is available, but not used.

B. Hydrograph and Routing
- Storage capacity behind a highway embankment attenuates a flood hydrograph and reduces the peak discharge.
- Significant storage will reduce the required culvert size. However, the storage should not create a state class dam.
- Is checked by routing the design hydrographs through the culvert site to determine the outflow hydrograph and stage (backwater) behind the culvert.
- Procedures are in HDS 5, Section V.
- Must be of a permanent nature, and
- May only be used by approval of the Drainage Section.

Computational Methods

Nomographs

- Require a trial and error solution that is quite easy and provides reliable designs for many applications.
- Require additional computations for tailwater, outlet velocity, hydrographs, routing and roadway overtopping.
- Circular and box shapes are included in the appendix of this chapter. Other shapes and improved inlets are found in HDS 5.

8.2 Design Goals & Guidelines (continued)

Computational Methods (continued)

Computer Software

HY8 (FHWA Culvert Analysis Software)
- Uses the theoretical basis for the nomographs.
- Can compute tailwater, improved inlets, road overtopping, hydrographs, routing and multiple independent barrels.
- Develops and plots tailwater rating curves.
- Develops and plots performance curves.

Other computer programs may be used, they must use the methodology presented in HDS 5. The designer shall check with the ADOT Drainage section prior to use. Comparison of computer program results with HDS 5 nomographs may be required.

8.3 Design Equations

8.3.1 General

An exact theoretical analysis of culvert flow is extremely complex because the following is required:
- analyzing nonuniform flow with regions of both gradually varying and rapidly varying flow,
- determining how the flow type changes as the flow rate and tailwater elevations change,
- applying backwater and drawdown calculations, energy and momentum balance,
- applying the results of hydraulic model studies, and
- determining if hydraulic jumps occur and if they are inside or downstream of the culvert barrel

8.3.2 Approach

The procedures in this chapter use the following:

Control Section

The control section is the location where there is a unique relationship between the flow rate and the upstream water surface elevation. Inlet control is governed by the inlet geometry. Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics and the tailwater.

Minimum Performance

Minimum performance is assumed by analyzing both inlet and outlet control and using the highest headwater. The culvert may operate more efficiently at times (more flow for a given headwater level), but it will not operate at a lower level of performance than calculated.

8.3 Design Equations (continued)

8.3.3 Inlet Control

For inlet control, the control section is at the upstream end of the barrel (the inlet). The flow passes through critical depth near the inlet and becomes shallow, high velocity (supercritical) flow in the culvert barrel. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

Headwater Factors

- Headwater depth is measured from the inlet invert of the inlet control section to the surface of the upstream pool.
- Inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area.
- Inlet edge configuration describes the entrance type. Some typical inlet edge configurations are thin edge projecting, mitered, square edges in a headwall and beveled edge.
- Inlet shape is usually the same as the shape of the culvert barrel. Typical shapes are rectangular, circular, elliptical and arch. Check for an additional control section, if different than the barrel.

Hydraulics

Three regions of flow are shown in the Figure 8-1: unsubmerged, transition and submerged:

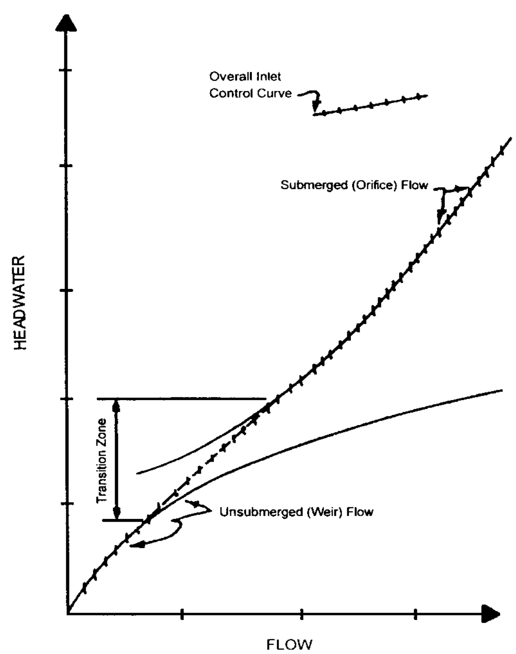


Figure 8-1 Unsubmerged, Transition And Submerged

8.3 Design Equations (continued)

8.3.3 Inlet Control (continued)

Unsubmerged

For headwater below the inlet crown, the entrance operates as a weir.

- A weir is a flow control section where the upstream water surface elevation can be predicted for a given flow rate.
- The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges.
- These tests are then used to develop equations. Appendix A of HDS 5 contains the equations which were developed from model test data, see Figure 8-2, Unsubmerged:

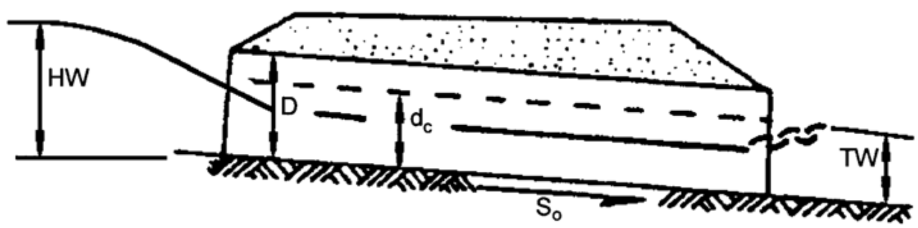


Figure 8-2 Unsubmerged

Submerged

For headwaters above the inlet, the culvert operates as an orifice.

- An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section.
- The relationship between flow and headwater can be defined based on results from model tests. Appendix A of HDS 5 contains flow equations that were developed from model test data. See Figure 8-3, Submerged.

Transition Zone

The transition zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves.

8.3 Design Equations (continued)

8.3.3 Inlet Control (continued)

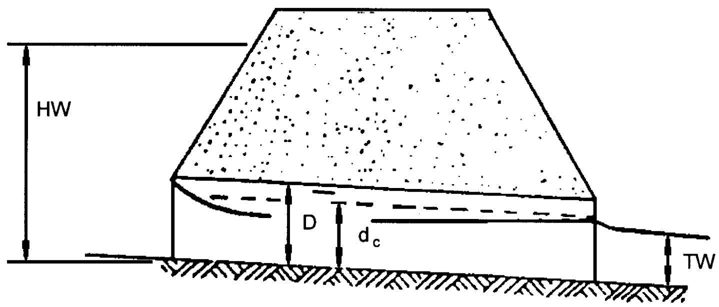


Figure 8-3 Submerged

Nomographs

The inlet control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs. Note that in the inlet control nomographs, HW is measured to the total upstream energy grade line including the approach velocity head.

8.3.4 Outlet Control

Outlet control has depths and velocity that are subcritical. The control of the flow is at the downstream end of the culvert (the outlet). The tailwater depth is either assumed to be critical depth near the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the barrel factors. All of the inlet control factors also influence culverts in outlet control.

Barrel Roughness

Barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by a hydraulic resistance coefficient such as the Manning n value. Typical Manning n values for pipe materials are presented in Appendix B.

Barrel Area

Barrel area is measured perpendicular to the flow.

8.3 Design Equations (continued)

8.3.4 Outlet Control (continued)

Barrel Length

Barrel length is the total culvert length from the entrance crown to the exit crown of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.

Barrel Slope

Barrel slope is the actual slope of the culvert barrel, and is often the same as the natural stream slope. However, when the culvert inlet or outlet is raised or lowered, the barrel slope is different from the stream slope.

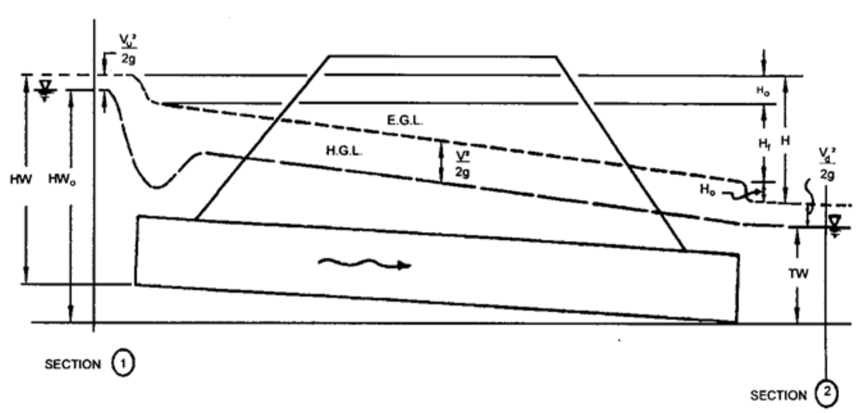
Tailwater Elevation

Tailwater is based on the downstream water surface elevation. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation (see Section 8.3.3).

Hydraulics

Full flow in the culvert barrel is assumed for the analysis of outlet control hydraulics. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool

Figure 8-4 Outlet Control Flow, TW ≥ D



8.3 Design Equations (continued)

8.3.4 Outlet Control (continued)

Losses: $\mathbf{H_L = H_E + H_f + H_o + H_b + H_j + H_g}$ **(8.1)**

Where:
- H_L = total energy loss, ft.
- H_E = entrance loss, ft.
- H_f = friction losses, ft.
- H_o = exit loss (velocity head), ft.
- H_b = bend losses, ft. (see HDS 5)
- H_j = losses at junctions, ft. (see HDS 5)
- H_g = losses at grates, ft. (see HDS 5)

Velocity: $\mathbf{V = Q/A}$ **(8.2)**

Where:
- V = average barrel velocity, ft/sec
- Q = flow rate, ft^3/sec
- A = cross sectional area of flow with the barrel full, ft^2

Velocity head: $\mathbf{H_v = V^2/2g}$ **(8.3)**

Where: g = acceleration due to gravity, 32.2 ft/sec^2

Entrance loss: $\mathbf{H_E = K_E\,(V^2/2g)}$ **(8.4a)**

Where: K_E = entrance loss coefficient, see table in Appendix B

Friction loss: $\mathbf{H_f = [(29n^2L)/R^{1.33}]\,[V^2/2g]}$ **(8.4b)**

Where:
- n = Manning's roughness coefficient, see table in Appendix B
- L = length of the culvert barrel, ft.
- R = hydraulic radius of the full culvert barrel = A/P, ft.
- P = wetted perimeter of the barrel, ft.

Exit loss: $\mathbf{H_o = 1.0\,[(V^2/2g) - (V_d^{\,2}/2g)]}$ **(8.4c)**

Where: V_d = channel velocity downstream of the culvert, ft./sec (usually neglected, see equation 8.4d).

$\mathbf{H_o = H_v = V^2/2g}$ **(8.4d)**

Barrel losses: $\mathbf{H = H_E + H_o + H_f}$

$\mathbf{H = [1 + K_e + (19.63n^2L/R^{1.33})]\,[V^2/2g]}$ **(8.5)**

8.3 Design Equations (continued)

8.3.4 Outlet Control (continued)

Energy Grade Line

The energy grade line represents the total energy at any point along the culvert barrel. Equating the total energy at sections 1 and 2, upstream and downstream of the culvert barrel in Figure 8-4, the following relationship results:

$$\mathbf{HW_o+(V_u^2/2g) = TW+(V_d^2/2g)+H_L} \tag{8.6}$$

Where:
- HW_o = headwater depth above the outlet invert, ft.
- V_u = approach velocity, ft./sec
- TW = tailwater depth above the outlet invert, ft.
- V_d = downstream velocity, ft/sec
- H_L = sum of all losses (equation 8.1)

Hydraulic Grade Line

The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel lines separated by the velocity head except at the inlet and the outlet.

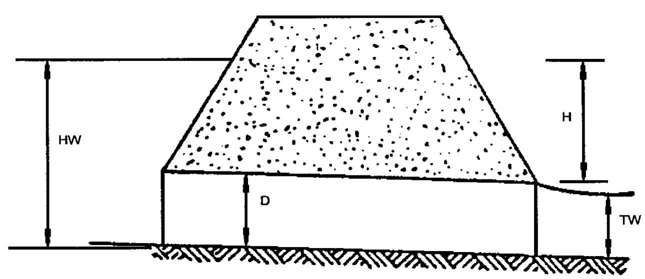


Figure 8-5 Outlet Control, TW = D

8.3 Design Equations (continued)

8.3.4 Outlet Control (continued)

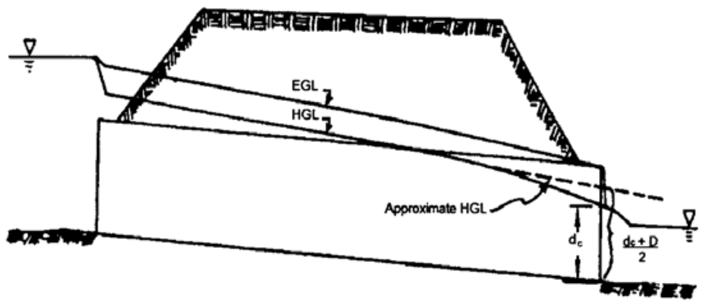


Figure 8-6 Outlet Control, TW < d_c

Nomographs (full flow)

The nomographs were developed assuming that the culvert barrel is flowing full and:

- $TW \geq D$, (see Figure 8-4) or
- $d_c \geq D$, (see Figure 8-5)
- V_u is small and its velocity head can be considered to be a part of the available headwater (HW) used to convey the flow through the culvert.
- V_d is small and its velocity head can be neglected.

Equation (8.6) becomes:

$$\mathbf{HW = TW + H - S_oL} \qquad \mathbf{(8.7)}$$

Where: HW = depth from the inlet invert to the energy grade line, ft.
H = is the value read from the nomographs (equation 8.5), ft.
S_oL = drop from inlet to outlet invert, ft.

Nomographs (Partly full flow)

Equations (8.1) through (8.7) were developed for full barrel flow. The equations also apply to the flow situations which are effectively full flow conditions, if TW < d_c, Figure 8-6.

- Backwater calculations may be required which begin at the downstream water surface and proceed upstream. If the depth intersects the top of the barrel, a full flow extends from that point upstream to the culvert entrance.

8.3 Design Equations (continued)

8.3.4 Outlet Control (continued)

Nomographs (Partly full flow) - Approximate method

Based on numerous backwater calculations performed by the FHWA staff, it was found that the hydraulic grade line pierces the plane of the culvert outlet at a point approximately one-half way between critical depth and the top of the barrel or $(d_c + D)/2$ above the outlet invert. TW should be used if higher than $(d_c + D)/2$. The following equation should be used:

$$\mathbf{HW = h_o + H - S_oL} \qquad \mathbf{(8.8)}$$

Where: h_o = the larger of TW or $(d_c + D)/2$, ft.

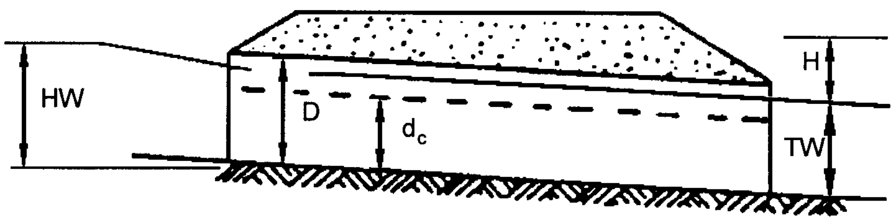
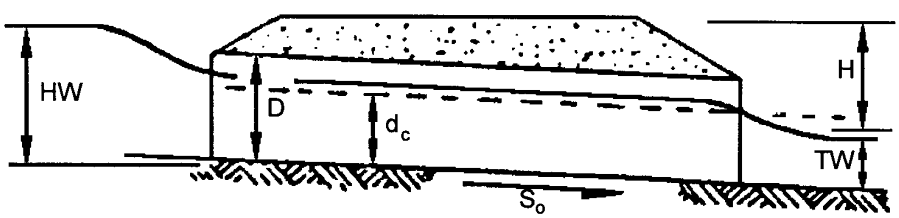


Figure 8-7 Outlet Control, TW < d_c

Adequate results are obtained down to a HW = 0.75D. For lower headwaters, backwater calculations are required. (See Figure 8-7 if TW < d_c and Figure 8-8 if TW > d_c)

Figure 8-8 Outlet Control, TW > d_c



8.3 Design Equations (continued)

8.3.5 Outlet Velocity

Culvert outlet velocities shall be calculated to determine need for erosion protection at the culvert exit. Culverts usually result in outlet velocities that are higher than the natural stream velocities. These outlet velocities may require flow readjustment or energy dissipation to prevent downstream erosion. If outlet erosion protection is necessary, the flow depths and Froude number may also be needed (see Chapter 9, Energy Dissipators).

Inlet Control

The velocity is calculated from equation 8.2 after determining the outlet depth. Either of the following methods may be used to determine the outlet depth.

- Calculate the water surface profile through the culvert. Begin the computation at d_c at the entrance and proceed downstream to the exit. Determine at the exit the depth and flow area.
- Assume normal depth and velocity. This approximation may be used if the culvert is of adequate length so that the water surface profile converges towards normal depth. This outlet velocity may be slightly higher than the actual velocity at the outlet. Normal depths may be obtained from design aids in Chapter 7. If the culvert is steep and sufficiently long that normal depth occurs, high tailwater may force a hydraulic jump. It may be necessary to evaluate the location of the hydraulic jump.

Outlet Control

The cross sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth, or the height of the conduit.

- Critical depth is used when the tailwater is less than critical depth.
- Tailwater depth is used when tailwater is greater than critical depth, but below the top of the barrel.
- The total barrel area is used when the tailwater exceeds the top of the barrel.

8.3.6 Roadway Overtopping

Roadway overtopping will begin when the headwater rises to the elevation of the roadway. The overtopping will usually occur at the low point of a sag vertical curve on the roadway. The flow will be similar to flow over a broad crested weir. Flow coefficients for flow overtopping roadway embankments are found in Hydraulic Design of Highway Culverts, HDS No. 5. For flow overtopping a median barrier, the weir will no longer function as a broad crested weir. H must be measured from the top of barriers.

8.3 Design Equations (continued)

8.3.6 Roadway Overtopping (continued)

$$\mathbf{Q_r = C_d\ L\ HW_r^{1.5}} \qquad \textbf{(8.9)}$$

Where: Q_r = overtopping flow rate, ft^3/sec
C_d = overtopping discharge coefficient (weir coefficient) = $k_t\ C_r$
k_t = submergence coefficient
C_r = discharge coefficient
L = length of the roadway crest, ft.
HW_r = the upstream depth, measured above the roadway crest, ft.

Height

The height is measured above the point where the flow "crests" over the "dam". It may be the top of guardrail or barrier, if these are present.

Length

The length is difficult to determine when the crest is defined by a roadway sag vertical curve.

- Recommend subdividing into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are added together to determine the total flow.
- The length can be represented by a single horizontal line (one segment). The length of the weir is the horizontal length of this segment. The depth is the average depth (area/length) of the upstream pool above the roadway.

Total Flow

- Roadway overflow plus culvert flow must equal total design flow.
- Roadway overflow is calculated for a given upstream water surface elevation using equation 8.9
- A trial and error process is necessary to determine the flow passing through the culvert and the amount flowing across the roadway.

8.3.7 Performance Curves

Performance curves are plots of flow rate versus headwater depth or elevation, velocity, or outlet scour. The culvert performance curve is made up of the controlling portions of the individual performance curves for each of the following control sections. Performance curves for the culvert and the road overflow may be summed to yield an overall performance. (See Figure 8-9):

Inlet

The inlet performance curve is developed using the inlet control nomographs. (see Appendix A).

Outlet

The outlet performance curve is developed using equations 8.1 through 8.7, the outlet control nomographs (see Appendix A), or backwater calculations.

8.3 Design Equations (continued)

8.3.7 Performance Curves (continued)

Roadway

Roadway performance curve is developed using equation 8.9.

Overall

Overall performance curve is the sum of the flow through the culvert and the flow across the roadway and can be determined by performing the following steps.

1. Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters may need to be calculated.

2. Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.

3. When the culvert headwater elevations exceed the roadway crest elevation, overtopping will begin. Calculate the upstream water surface depth above the roadway for each selected flow rate. Use these water surface depths and equation 8.9 to calculate flow rates across the roadway.

4. Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve as shown in Figure 8-9.

8.3 Design Equations (continued)

8.3.7 Performance Curves (continued)

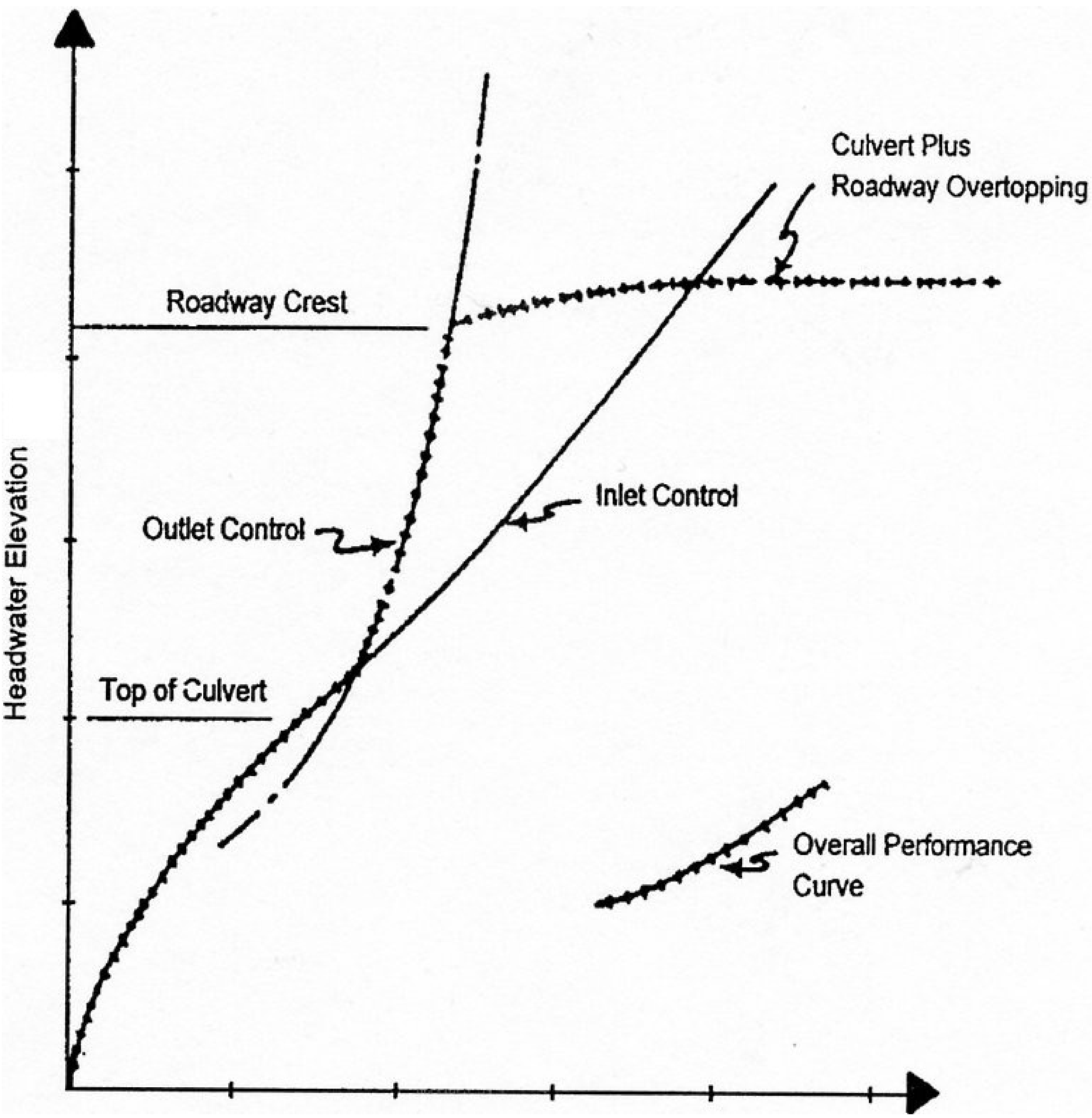


Figure 8-9 Overall Performance Curve

8.4 Design Procedure

The following design procedure provides a convenient and organized method for designing culverts for a constant discharge, considering inlet and outlet control. The procedure does not address the affect of storage which is discussed in the Storage Chapter.

- The designer should be familiar with all the equations in Section 8.3 before using these procedures.
- Following the design method without an understanding of culvert hydraulics can result in an inadequate, unsafe, or costly structure.
- The computation form has been provided in Appendix B to guide the user. It contains blocks for the project description, designer's identification, hydrologic data, culvert dimensions and elevations, trial culvert description, inlet and outlet control HW, culvert barrel selected and comments.

Step 1 Assemble Site Data And Project File

a. See Data Chapter — The minimum data are:
- site and location maps, USGS,
- embankment cross section,
- roadway profile,
- field visit (sediment, debris)

Desirable Data includes
- photographs, and
- design data at nearby structures.

b. Studies by other agencies including:
- small dams -- NRCS, USCE, BLM,
- canals -- NRCS, USCE, USBR, SRP
- floodplain -- FEMA, NRCS, USCE, USGS, and Flood Control Districts, and
- storm drain -- local or private.

c. Environmental constraints including:
- commitments contained in project and environmental documents,

Design criteria
- allowable headwater elevation
- allowable outlet velocity.

Step 2 Determine Hydrology

a. Determine flood frequency from criteria.
b. Identify discharges to be used in determining culvert size.

8.4 Design Procedure (continued)

Step 3 Evaluate Downstream Channel

a. Determine tailwater depth/elevation information
b. Minimum data are cross section of channel and the rating curve for channel.

Step 4 Summarize Data On Design Form

a. See Chart in Appendix B.
b. Data from steps 1-3.

Step 5 Identify Design Alternative

a. Choose culvert material, shape, size and entrance type.

Step 6 Select Design Discharge Q_d

a. Divide design Q by the number of barrels.

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use the inlet control nomograph (Appendix A).

a. Locate the size or height on the scale.
b. Locate the discharge.
- For a circular shape use discharge.
- For a box shape use Q per foot of width.

c. Locate HW/D ratio.
- Use a straight edge.
- Extend a straight line from the culvert size through the flow rate.
- Mark the first HW/D scale. Extend a horizontal line to the desired scale and read HW/D and note on Culvert Design Form (Appendix B).
- If the design case falls above the nomograph, the trial culvert size is too small.
- If the line falls below the nomograph, the trial culvert size is too large. Sometimes the minimum culvert size is controlled by factors other than hydraulics. If a calculated headwater surface is needed, see discussion in Appendix D.

d. Calculate headwater depth (HW_i).
- Multiply HW/D by D to obtain HW to energy gradeline.
- Neglecting the approach velocity HW_i = HW.
- Including the approach velocity HW_i = HW - approach velocity head.

8.4 Design Procedure (continued)

Step 8 Determine Outlet Control Headwater Depth At Inlet (HW_{oi})

a. Calculate the tailwater depth (TW) using the design flow rate and normal depth (single section) or using a water surface profile.
b. Calculate critical depth (d_c) using appropriate chart in Appendix A.

- Locate flow rate and read d_c.
- d_c cannot exceed D.
- If $d_c > 0.9D$, consult Handbook of Hydraulics (King and Brater) for a more accurate d_c, if needed, since curves are truncated where they converge.

c. Calculate $(d_c + D)/2$.

d. Determine (h_o).
h_o = the larger of TW or (d_c + D/2).
e. Determine (K_E).

- Entrance loss coefficient from Table 2 in the Appendix B.

f. Determine losses through the culvert barrel (H).

- Use nomograph (Appendix A) or equation 8.5 or 8.6 if outside range.
- Locate appropriate K_E scale.
- Locate culvert length (L) or (L_1):
  - use (L) if Manning's n matches the n value of the culvert and
  - use (L_1) to adjust for a different culvert n value.

$$\mathbf{L_1 = L(n_1/n)^2} \qquad \textbf{(8.10)}$$

Where: L_1= adjusted culvert length, ft
L = actual culvert length, ft
n_1 = desired Manning n value
n = Manning n value on chart

Mark point on turning line:
- use a straight edge and
- connect size with the length.

- Read (H):
  - use a straight edge,
  - connect Q and turning point and
  - read (H) on Head Loss scale.

g. Calculate outlet control headwater (HW_{oi}).

- Use equation 8.11, if V_u and V_d are neglected:

$$\mathbf{HW_{oi} = H + h_o - S_oL} \qquad \textbf{(8.11)}$$

- Use equation 8.1, 8.4c and 8.6 to include V_u and V_d.

8.4 Design Procedure (continued)

Step 8 Determine Outlet Control Headwater Depth At Inlet (HW_{oi}) (continued)

g. Calculate outlet control headwater (HW_{oi}). (continued)

- If HW_{oi} is less than 1.2D and control is outlet control:
  - the barrel may flow partly full,
  - the approximate method of using the greater of tailwater or $(d_c + D)/2$ may not be applicable,
  - backwater calculations should be used to check the result and
  - if the headwater depth falls below 0.75D, the approximate nomograph method shall not be used. A backwater analysis can be performed from the outlet to just inside the inlet and the ponded Headwater can be directly computed. See Appendix D.

Step 9 Determine Controlling Headwater (HW_c)

- Compare HW_i and HW_{oi}, use the higher as HW_c.

Step 10 If appropriate, Compute Discharge Over The Roadway (Q_r)

a. Calculate depth above the roadway (HW_r).

$HWr = HW_c - HW_{ov}$

HW_{ov} = height of road above inlet invert

b. If $HW_r <= 0$, $Q_r = 0$

If $HW_r > 0$, determine C_d from Appendix D

c. Determine length of roadway crest (L).

d. Calculate Q_r using equation 8.12.

$$\mathbf{Q_r = C_d\, L\, HW_r^{1.5}} \qquad \textbf{(8.12)}$$

Step 11 Compute Total Discharge (Q_t)

$$\mathbf{Q_t = Q_d + Q_r} \qquad \textbf{(8.13)}$$

Step 12 Calculate Outlet Velocity (V_o) And Depth (d_n)

If inlet control is the controlling headwater:

a. Calculate flow depth at culvert exit.

- use normal depth (d_n) or
- use water surface profile

b. Calculate flow area (A).

8.4 Design Procedure (continued)

Step 12 Calculate Outlet Velocity (V_o) And Depth (d_n) (continued)

c. Calculate exit velocity (V_o) = Q/A.

If outlet control is the controlling headwater:

a. Calculate flow depth at culvert exit.
   - use (d_c) if $d_c > TW$
   - use (TW) if $d_c < TW < D$
   - use (D) if $D < TW$

b. Calculate flow area (A).

c. Calculate exit velocity (V_o) = Q/A.

Step 13 Review Results

Compare alternative design with constraints and assumptions. If any of the following are exceeded, repeat steps 5 through 12:

- the barrel must have adequate cover,
- the length shall be close to the approximate length,
- the headwalls and wingwalls must fit site,
- the allowable headwater shall not be exceeded, and
- the allowable overtopping flood frequency shall not be exceeded.

Step 14 If needed, Plot Performance Curve

a. Repeat steps 6 through 12 with a range of discharges.
b. Use the following upper limit for discharge:
   - Q_{100} if $Q_o <= Q_{100}$
   - Q_{500} if $Q_o > Q_{100}$

Step 15 Related Designs

Consider the following options (See Sections 8.3.4 and 8.3.5).

- Energy dissipators if V_o is larger than the normal V in the downstream channel (See Energy Dissipator Chapter).
- Sediment control storage for sites with sediment concerns such as alluvial fans (See Erosion and Sediment Control Chapter and Appendix C).

Step 16 Documentation

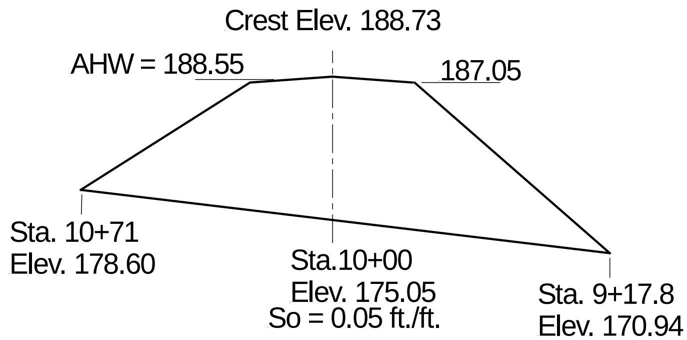
- See Documentation Chapter.
- Prepare report and file with background information.

8.5 Nomograph Design Example

The following example problem follows the Design Procedure Steps described in Section 8.4

Step 1 Assemble Site Data And Project File

a. Site survey Project file contains:
- USGS, site, and location maps,
- roadway profile, and
- embankment cross-section



Site visit notes indicate:
- no sediment or debris problems, and
- no nearby structures.

b. Studies by other agencies - none

c. Environmental, risk assessment shows:
- no buildings near floodplain,
- no sensitive floodplain values,
- no FEMA involvement, and
- convenient detours exist.

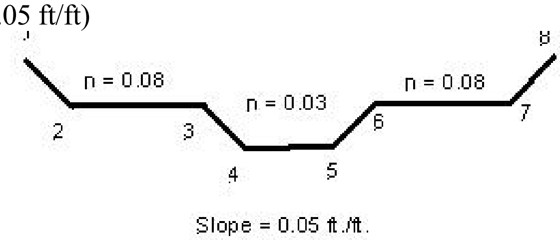
d. Design criteria:
- 50-year frequency for design, and
- 100-year frequency for overtopping check.

Step 2 Determine Hydrology

From file:
- Q_{50} = 600 cfs
- Q_{100} = 750 cfs

Step 3 Design Downstream Channel

Cross section of channel (Slope = .05 ft/ft)



8.5 Nomograph Design Example (continued)

Step 3 Design Downstream Channel (continued)

Point	Station, ft	Elevation, ft
1	12	180
2	22	175
3	32	174.5
4	34	172.5
5	39	172.5
6	41	174.5
7	51	175
8	61	180

The rating curve for the channel calculated by normal depth yields:

Q (cfs)	Elev. (ft.)	TW (ft)	V (ft/s)
0	172.50	0	0
75	173.70	1.7	10.23
150	174.28	1.78	12.52
225	174.69	2.19	14.35
300	174.99	2.49	15.94
375	175.23	2.73	17.17
450	175.43	2.93	18.18
525	175.63	3.13	19.10
600	175.80	3.30	19.92
675	175.97	3.47	20.68
750	176.12	3.62	21.39

Step 4 Summarize Data On Design Form

See Figure 8-10

Step 5 Select Design Alternative

Shape-box
Size – Minimum height = 6 ft
Material - concrete, n = .012
Entrance –beveled

Use Chart 9-2

Step 6 Select Design Discharge ($Q_d = Q_{50}$ = 600 cfs)

8.5 Nomograph Design Example (continued)

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use inlet control nomograph - Chart 9 column 2
a. D = 6 ft

b. Allowable headwater = 188.55 – 177.19= 11.36'
trial H_W/D = 11.36/6.0 = 1.89
from Chart 9-2. q/B = 96 cfs.
therefore, B_{min}= 600/96 = 6.25', use 8'
q/B = 600/8 = 75 cfs. OK.
H_W/D = 1.45. H_W = 1.45*6 = 8.7'

Step 8 Determine Outlet Control Headwater Depth At Inlet (HW_{oi})

a. TW = 3.3 ft for Q_{50} = 600 cfs
b. for q = 75 cfs, d_c = 5.6 ft from Chart 14, 4.8' < 6' OK.
c. $(d_c + D)/2 = (5.6' + 6')/2 = 5.8$ ft.
d. h_o = the larger of TW or $(d_c + D/2)$
$h_o = (d_c + D)/2 = 5.80$ ft
e. K_E = 0.2 from Table 2
f. Determine (H) - use Chart 15
- K_E scale = 0.2
- culvert length (L) = 93.8 ft, see page 8-33
- n = .012 same as on chart
- area = 48 ft^2
- H = 3.4 ft

g. $HW_{oi} = H + h_o - S_oL$ = 3.4′ + 5.80′ - (.05)*93.8' = 4.41'
HW_{oi} is less than 1.2D, but control is inlet control.
Outlet control computations are for comparison only.

Step 9 Determine Controlling Headwater (HW_c)

- $HW_c = HW_i$ = 8.7 ft > HW_{oi} = 4.41 ft
- The culvert is in inlet control.

Step 10 Compute Discharge Over The Roadway (Q_r)

a. Calculate depth above the roadway:
$HWr = HW_c - HW_{ov}$ = 8.7′ - 11.36′ = - 2.66 ft
b. If $HW_r \leq 0$, $Q_r = 0$

Step 11 Compute Total Discharge (Q_t)

$Q_t = Q_d + Q_r$ = 600 cfs + 0 = 600 cfs

8.5 Nomograph Design Example (continued)

Step 12 Calculate Outlet Velocity (V_o) And Depth (d_n)

INLET CONTROL

a. Calculate normal depth (d_n):
   $Q = (1.49/n)A\ R^{2/3}\ S^{1/2} = 600$ cfs
   $= 124.2(8*d_n)[8*d_n/(8+2d_n)]^{2/3}(.05)^{.5}$
   $= (8*d_n)[8*d_n/(8+2d_n)]^{2/3} = 600/(124.2*(.05)^{.5}) = 21.60$
   try $d_n = 2.0$ ft, $19.4 < 21.6$
   use $d_n = 2.16$ ft, $21.65 \approx 21.6$
b. $A = 2.16*8 = 17.28\ ft^2$
c. $V_o = Q/A = 600/17.28 = 34.7$ ft/s

Step 13 Review Results

Compare alternative design with constraints and assumptions. If any of the following are exceeded repeat, steps 5 through 12:

- headwalls and wingwalls fit site,
- allowable headwater, 11.36 ft > 8.7 ft is OK, and
- overtopping flood frequency > 50-year.

Step 14 Plot Performance Curve

Use Q_{100} for the upper limit. Steps 6 through 12 should be repeated for each discharge used to plot the performance curve. These computations are provided on the computation form that follows this example (see Figure 8-10).

Step 15 Related Designs

Consider the following options (see sections 9.3.4 and 9.3.5).

- Consider tapered inlets, culvert is in inlet control and has limited available headwater.
- No flow routing, a small upstream headwater pool exists.
- Consider energy dissipators since V_o = 35 ft/s > 18 ft/s in the downstream channel.
- No sediment problem.
- No fishery.

Step 16 Documentation

Prepare Report and file with background information

8.5 Nomograph Design Example (continued)

Project Name ____ADOT Hydraulics Manual__________ Proj. No. __ADT064__________
Station/Location __Example 1__________ Designer_G. Lopez-Cepero___ Date__2/11/04__
Subject __________ Checker__________ Date__________

Design Flows:

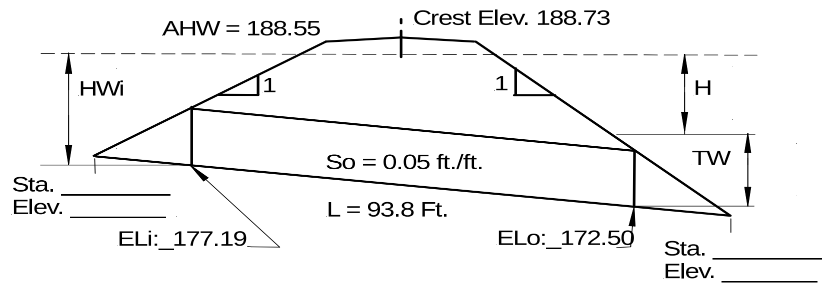
R.I (Years)	Flow (cfs)	T.W. (ft)
__50_____	_600____	_3.30___
__100____	_750____	_3.62___

For Table: $EL_{hi} = EL_i + Hw_i$

h_o = greater of TW or $(d_c+D)/2$

H from chart 15

$El_{ho} = El_o + h_o + H$



Culvert Description:	1-10x6 with Bevel Entrance														
Total Flow (cfs)	Flow/Ft: (cfs)	HEADWATER CALCULATIONS											Control HW:	Vo Ft/sec:	Comments
		Inlet Control: Chart 9				Outlet Control: Chart 15									
		Hw_i/D	Hw_i	Fall	EL_{hi}	TW	d_c	$(d_c+D)/2$:	h_o	k_e	H	EL_{ho}			
600	60	1.26	7.56	--	184.75	3.30	4.8	5.6	5.6	0.2	2.8	180.90	184.75	33	184.75<188.55 OK
750	75	1.50	9.0	--	186.19	3.62	5.6	5.8	5.8	0.2	4.4	182.70	186.19	36	186.19<188.73 OT does not occur
150	15	0.5	3.0	--	180.19										
300	30	0.78	4.68	--	181.87										
450	45	1.04	6.24	--	183.43										

Figure 8-10 Culvert Chart for Design Example

8.6 Microcomputer Solution

8.6.1 Overview

Culvert hydraulic analysis can also be accomplished with the aid of the microcomputer software. The following example has been produced using the HY-8 Culvert Analysis Microcomputer Program. This is a computer solution of the data provided in Section 8.5.

8.6.2 Data Input

In creating a data input file, the user will be prompted for the discharge range, site data and culvert shape, size, material and inlet type. The discharge range for this example will be from 0 to 750 cfs.

As each group of data is entered the user is allowed to edit any incorrect entries. The following is the summary of the culvert information given the program.

Culvert Data

Let us use a 6 ft x 6 ft concrete box culvert as our initial trial size. For the culvert use a conventional inlet with 1:1 bevels and 45-degree wingwalls. The site data is entered by providing culvert invert data. If embankment data points are input, the program will fit the culvert in the fill and subtract the appropriate length.

CULVERT FILE: MAN_6x6	FHWA CULVERT ANALYSIS	DATE:01-06-2004
TAILWATER FILE: MAN_6x6	HY-8, VERSION 6.0	CULVERT NO. 1 OF 1

ITEM	SELECTED CULVERT
(1) BARREL SHAPE:	BOX
(2) BARREL SIZE	6.00 FT X 6.00 FT
(3) BARREL MATERIAL:	CONCRETE
(4) MANNING'S n:	.012
(5) INLET TYPE:	CONVENTIONAL
(6) INLET EDGE AND WALL:	BEVELED EDGE (1.5:1)
(7) INLET DEPRESSION:	NONE

8.6 Microcomputer Solution (continued)

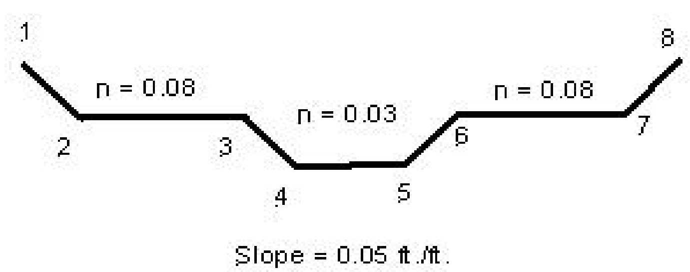
8.6.2 Data Input (continued)

Channel Data

Next the program will prompt for data pertaining to the channel so that tailwater elevations can be determined. Referring to the problem statement, the channel is irregularly shaped and can be described by the 8 coordinates listed. After opening the irregular channel file the user will be prompted for channel slope (.05), number of cross-section coordinates (8) and subchannel option. The subchannel option in this case would be option (2), left and right overbanks (n =.08) and main channel (n =.03).

The next prompt, for channel boundaries, refers to the number of the coordinate pair defining the left subchannel boundary and the number of the coordinate pair defining the right subchannel boundary. The boundaries for this example are the 3rd and 6th coordinates. After this is input, the program prompts for channel coordinates. Once these are entered, pressing (P) will cause the computer to display the channel cross-section shown below. The user can easily identify any input errors by glancing at the plot. To return to the data input screens, press any key. If data are correct press (return). The user can then enter the roughness data for the main channel and overbanks.

IRREGULAR CHANNEL CROSS-SECTION		
CROSS-SECTION	X	Y
COORD. NO	(FT.)	(FT.)
1	12	180
2	22	175
3	32	174.5
4	34	172.5
5	39	172.5
6	41	174.5
7	51	175
8	61	180



8.6 Microcomputer Solution (continued)

8.6.3 Rating Curve

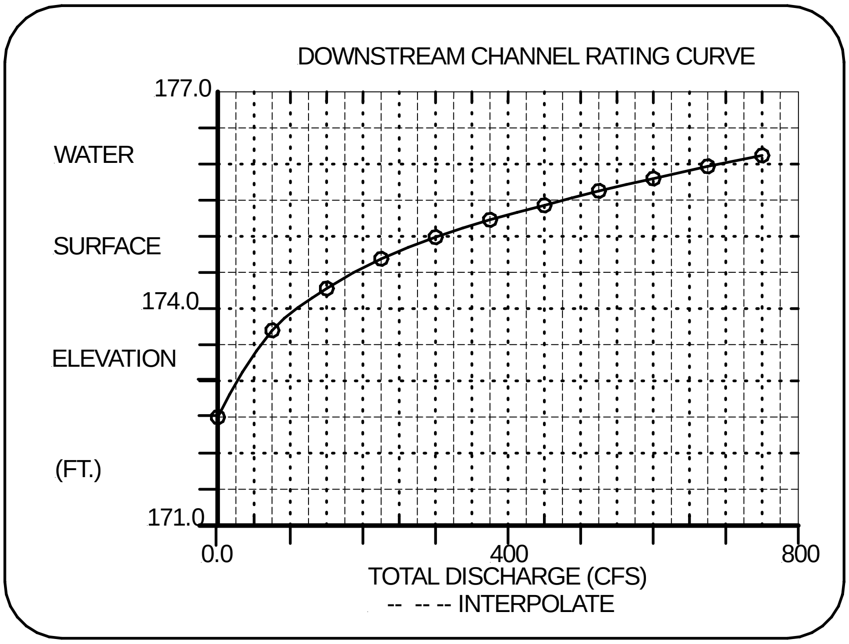
The program now has enough information to develop a uniform flow rating curve for the channel and provide the user with a list of options. Selecting option (T) on the Irregular Channel Data Menu will make the program compute the rating curve data and display the following table. Selecting option (I) will permit the user to interpolate data between calculated points.

[HY-8 screen]
TAILWATER RATING CURVE
IRREGULAR CHANNEL FILE: MAN_6

NO.	FLOW(CFS) (cfs)	W.S.E. (ft)	DEPTH (ft)	VEL. (f/s)	SHEAR (using R) (psf)
1	0.00	172.50	0.0	0.00	0.00
2	75.00	173.70	1.20	10.23	2.77
3	150.00	174.28	1.78	12.52	3.75
4	225.00	174.69	2.19	14.36	4.60
5	300.00	174.99	2.49	15.94	5.39
6	375.00	175.23	2.73	17.17	6.02
7	450.00	175.43	2.93	18.18	6.56
8	525.00	175.63	3.13	19.10	7.06
9	600.00	175.80	3.30	19.92	7.53
10	675.00	175.97	3.47	20.68	7.96
11	750.00	176.12	3.62	21.39	8.37

The Tailwater Rating Curve Table consists of tailwater elevation (W.S.E.), normal depth, natural channel velocity (Vel.) in feet per second, and the shear stress in pounds per square foot at the bottom of the channel for various flow rates. At the design flow rate of 600 cfs, the tailwater elevation will be 175.80 feet. The channel velocity will be 19.92 ft/s, and the shear will be 7.53 psf. This information is useful in the design of channel linings if they are needed. Entering (P) will cause the computer to display the rating curve for the channel. This curve, shown on the next page, is a plot of tailwater elevation vs. flow rate at the exit of the culvert.

8.6 Microcomputer Solution (continued)



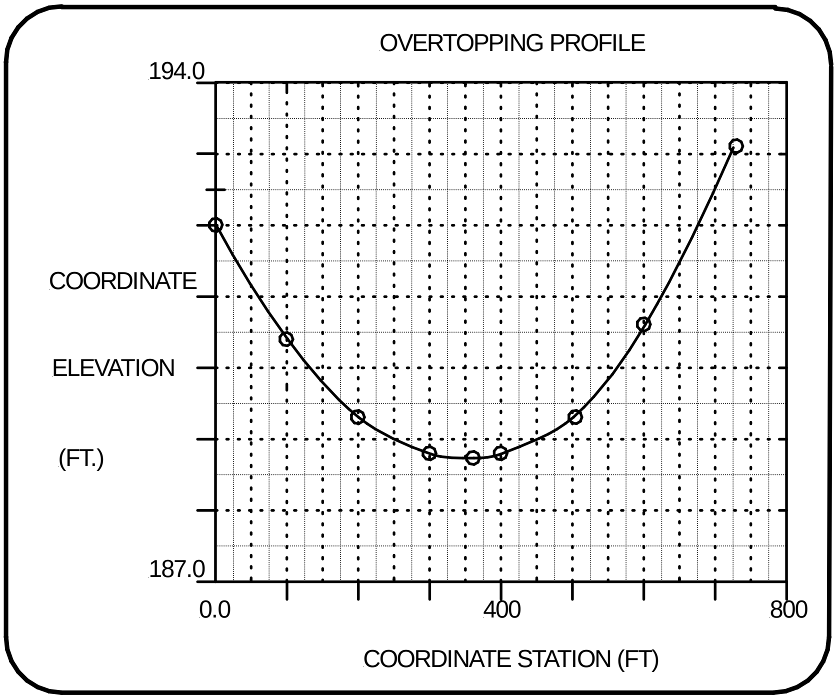
HY-8 Rating Curve

8.6.4 Roadway Data

The next prompts are for the roadway profile, so that an overtopping analysis can be performed. Referring to the problem statement, the roadway profile is a sag vertical curve, which will require nine coordinates to define. Once these coordinates are input, the profile will be displayed when (P) is entered, as illustrated below. The other data required for overtopping analysis are roadway surface or weir coefficient and the embankment top width. For this example, the roadway is paved with an embankment width of 50 feet.

ROADWAY PROFILE		
	STATION	ELEVATION
COORD. NO	(FT.)	(FT.)
1	0	192.0
2	100	190.4
3	200	189.3
4	300	188.8
5	360	188.73
6	400	188.8
7	500	189.3
8	600	190.6
9	720	193.1

8.6 Microcomputer Solution (continued)



HY-8 Overtopping Profile

8.6.5 Data Summary

All the data has now been entered and the summary table is displayed as shown below. At this point any of the data can be changed or the user can continue by pressing (Enter), which will bring up the Culvert Program Options Menu.

[HY-8 screen]

CULVERT FILE: MAN_6x6 FHWA CULVERT ANALYSIS DATE:01-06-2004
TAILWATER FILE: MAN_6x6 HY-8, VERSION 6.0 CULVERT NO. 1 OF 1
SUMMARY TABLE

C U L V NO.	A - SITE DATA INLET ELEV. (FT)	OUTLET ELEV. (FT)	CULVERT LENGTH (FT)	B - CULVERT SHAPE, MATERIAL, INLET BARRELS SHAPE MATERIAL	SPAN (FT)	RISE (FT)	MANN. n	INLET TYPE
1	177.19	172.50	93.93	1 - RCB	6.00	6.00	.012	CONV.
2								
3								

8.6 Microcomputer Solution (continued)

At this point, the program returns to the main menu. One may choose <S> Calculate or <M> Minimize. This feature, "Minimize Culvert Width" is intended to allow the designer to use HY-8 as a tool to perform culvert design for circular, box, elliptical, and arch shape culverts based on a user's defined allowable headwater elevation. This feature is activated by selecting letter "M". Once this letter is selected, the user inputs the allowable headwater elevation. That elevation will be the basis for adjusting the user's defined culvert size for the design discharge. The program will adjust the culvert span by increasing or decreasing by 0.5-foot increments. THE PROGRAM USES THE HEIGHT GIVEN; IT DOES NOT ADJUST THE HEIGHT OF THE CULVERT. It will compute the headwater elevation for the span, and compare it with the user's defined allowable headwater. If the computed headwater elevation is lower than or equal to the defined allowable headwater elevation the minimization routine will stop, and the adjusted culvert can be used for the remainder of the program.

8.6.6 Performance Curve (6 X 6)

At this point the data file can be saved or renamed by selecting option (S). The culvert performance curve table can be obtained by selecting option (N). If (N) is selected before (S) and an error occurs, the file can be retrieved by loading "current". When option (N) is selected, the program will compute the performance curve table without considering overtopping in the analysis. Since this 6 ft x 6 ft culvert is a preliminary estimate, the performance without considering overtopping is calculated and is shown below:

[HY-8 screen]

PERFORMANCE CURVE FOR CULVERT 1 - 1 (6.00 (ft) BY 6.00 (ft)) RCB

Q (cfs)	HWE (ft)	TWE (ft)	ICH (ft)		OCH (ft)	CCE (ft)	FCE (ft)	TCE (ft)	VO (ft/s)
0	177.19	172.50	0.00	-4.69	0.00	177.19	0.00	0.00	
75	179.61	173.70	2.42	-0.75	0.00	0.00	0.00	16.74	
150	181.13	174.28	3.94	0.04	0.00	0.00	0.00	19.33	
225	182.52	174.69	5.33	0.94	0.00	0.00	0.00	20.61	
300	183.87	174.99	6.68	1.99	0.00	0.00	0.00	21.98	
375	185.30	175.23	8.11	3.20	0.00	0.00	0.00	22.64	
450	186.90	175.43	9.71	4.58	0.00	0.00	0.00	23.42	
525	188.72	175.63	11.53		6.03	0.00	0.00	0.00	34.39
600	190.80	175.80	13.61		7.47	0.00	0.00	0.00	35.61
675	193.13	175.97	15.94		9.11	0.00	0.00	0.00	36.65
750	195.82	176.12	18.63		10.94	0.00	0.00	0.00	37.62

El. inlet face invert 177.19 ft El. outlet invert 172.50 ft
El. inlet throat invert 0.00 ft El. inlet crest 0.00 ft

This table indicates the controlling headwater elevation (HW), the tailwater elevation and the headwater elevations associated with all the possible control sections of the culvert. It is apparent from the table that at 600 cfs the headwater (HW) is 190.80 ft, which exceeds the design headwater of 188.73. Consequently, the 6 ft x 6 ft box culvert is inadequate to pass 600 cfs at the allowable headwater for the site conditions

8.6 Microcomputer Solution (continued)

8.6.7 Minimize Culvert

The user has the choice of using the minimize culvert or to select a new size by independent judgment. If minimize culvert is chosen, the program will request the allowable headwater elevation. The output is shown below. Several hydraulic parameters are also computed while performing the minimization routine. These hydraulic parameters which are part of the output of the minimization routine table, as shown below, must be printed from this screen because they are not printed with the output listing routine.

[HY-8 screen]

SUMMARY TABLE

C U L V NO.	A - SITE DATA INLET ELEV. (FT)	OUTLET ELEV. (FT)	CULVERT LENGTH (FT)	B - CULVERT SHAPE, MATERIAL, INLET BARRELS SHAPE MATERIAL	SPAN (FT)	RISE (FT)	MANN. n	INLET TYPE
1	177.190	172.50	93.93	1 - RCB	7.00	6.00	.012	CONV.

HEADWATER ELEVATION		FLOW VELOCITY		FLOW DEPTHS	
ENTER ALLOWABLE	= 188.73	CULVERT	= 35.29	CULVERT	= 2.43
CONTROLLING	= 188.45	CHANNEL	= 19.92	CHANNEL	= 3.30
INLET CONTROL	= 188.45	DISCHARGE	= 600.00	NORMAL	= 2.43
OUTLET CONTROL	= 182.96	SLOPE	= 0.0500	CRITICAL	= 6.00

MAX. HEADWATER <ENTER> TO CHANGE HEADWATER <ANY KEY> TO CONT.

This feature may be a time saver for designers because it avoids the need for repetitively editing a culvert size to obtain a controlling headwater elevation.

8.6 Microcomputer Solution (continued)

8.6.8 Trial 2, 8 x 6 Culvert

Since the design headwater criterion has not been met, another size must be selected. Based on the results of the minimize culvert, try an 8 ft x 6 ft culvert, and modify the file accordingly. The resulting performance table shown below indicates that the design headwater will not be exceeded at 600 cfs. However, the headwater elevation of 188.98 feet at 750 cfs indicates that some overtopping will occur due to the 100-year storm.

[HY-8 screen]

PERFORMANCE CURVE FOR CULVERT 1 - 1 (8.00 (ft) BY 6.00 (ft)) RCB

Q (cfs)	HWE (ft)	TWE (ft)	ICH (ft)	OCH (ft)	CCE (ft)	FCE (ft)	TCE (ft)	VO (ft/s)
0	177.19	172.50	0.00	-4.69	0.00	177.19	0.00	0.00
75	179.18	173.70	1.99	-0.94	0.00	0.00	0.00	15.88
150	180.38	174.28	3.19	-0.37	0.00	0.00	0.00	18.51
225	181.49	174.69	4.30	0.24	0.00	0.00	0.00	19.90
300	182.52	174.99	5.33	0.92	0.00	0.00	0.00	20.96
375	183.53	175.23	6.34	1.68	0.00	0.00	0.00	21.75
450	184.57	175.43	7.38	2.52	0.00	0.00	0.00	22.46
525	185.68	175.63	8.49	3.46	0.00	0.00	0.00	23.43
600	186.90	175.80	9.71	4.49	0.00	0.00	0.00	23.64
675	188.25	175.97	11.06	5.58	0.00	0.00	0.00	36.03
750	189.73	176.12	12.54	6.58	0.00	0.00	0.00	37.18

El. inlet face invert 177.19 ft El. outlet invert 172.50 ft
El. inlet throat invert 0.00 ft El. inlet crest 0.00 ft

8.6 Microcomputer Solution (continued)

8.6.9 Overtopping Performance Curve

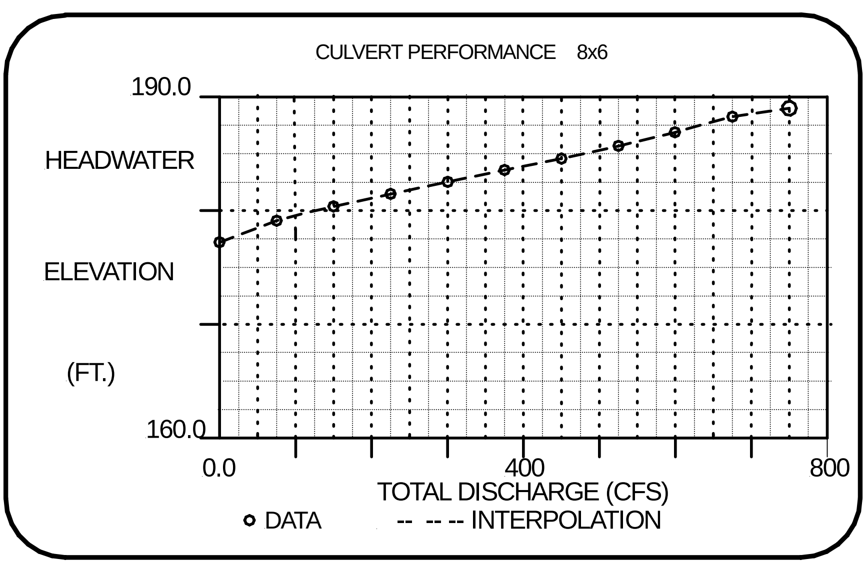
When overtopping occurs, the performance of the culvert will differ from that without overtopping. By selecting option (2), the culvert performance data can be obtained. The user also has the option to plot these data. To determine the amount of overtopping and the actual headwater, press (return), and then select (O) for overtopping. A Summary of Culvert Flows will appear on the screen, as shown below:

[HY-8 screen]

SUMMARY OF CULVERT FLOWS (CFS) FILE: MAN_8X6 DATE: 01-06-2004

ELEV(FT)	TOTAL	1	2	3	4	5	6	OT	ITER
177.19	0	0	0	0	0	0	0	0	0
179.18	75	75	0	0	0	0	0	0	1
180.38	150	150	0	0	0	0	0	0	1
181.49	225	225	0	0	0	0	0	0	1
182.52	300	300	0	0	0	0	0	0	1
183.53	375	375	0	0	0	0	0	0	1
184.57	450	450	0	0	0	0	0	0	1
185.68	525	525	0	0	0	0	0	0	1
186.90	600	600	0	0	0	0	0	0	1
188.25	675	675	0	0	0	0	0	0	1
188.98	750	713	0	0	0	0	0	34	6

This computation table is used when overtopping and/or multiple culvert barrels are used. It shows the headwater, total flow rate, the flow through each barrel and overtopping flow, and the number of iterations it took to balance the flows. From this information a total (culvert and overtopping) performance curve can be obtained by selecting option (1). This curve is a plot of the headwater elevation vs. the total flow rate which indicates how the culvert or group of culverts will perform over the selected range of discharges.



Performance curve

8.6 Microcomputer Solution (continued)

8.6.10 Review

From the Summary table, when the total flow is 750 cfs, 716 cfs passes through the culvert and 34 cfs flows over the road. The headwater elevation will be 188.98 feet. Assume that in this case overtopping at 100-year frequency can be tolerated, and the 8 ft x 6 ft culvert will be used. Referring back to the performance curve data, the outlet velocity at 600 cfs is 23.6 ft/s.

[HY-8 screen]

CULVERT # 1 PERFORMANCE CURVE NUMBER 1 BARREL(S)

Q (cfs)	HWE (ft)	TWE (ft)	ICH (ft)	OCH (ft)	CCE (ft)	FCE (ft)	TCE (ft)	VO (ft/s)
0	177.19	172.50	0.00	-4.69	0.00	177.19	0.00	0.00
75	179.18	173.70	1.99	-0.94	0.00	0.00	0.00	15.88
150	180.38	174.28	3.19	-0.37	0.00	0.00	0.00	18.51
225	181.49	174.69	4.30	0.24	0.00	0.00	0.00	19.90
300	182.52	174.99	5.33	0.92	0.00	0.00	0.00	20.96
375	183.53	175.23	6.34	1.68	0.00	0.00	0.00	21.75
450	184.57	175.43	7.38	2.52	0.00	0.00	0.00	22.46
525	185.68	175.63	8.49	3.46	0.00	0.00	0.00	23.43
600	186.90	175.80	9.71	4.49	0.00	0.00	0.00	23.64
675	188.25	175.97	11.06	5.58	0.00	0.00	0.00	36.03
712.85	188.98	176.12	11.79	6.07	0.00	0.00	0.00	36.60

El. inlet face invert	187.50 ft	El. outlet invert	172.50 ft
El. inlet throat invert	0.00 ft	El. inlet crest	0.00 ft

8.7 References

Norman, J.M., R.J. Houghtalen, and W.J. Johnston. Hydraulic Design of Highway Culverts, HDS No. 5, FHWA-IP-85-15, FHWA, Washington, D.C. 20590. 1985.

Young, G.K., and J.S. Krolak. HYDRAIN — Integrated Drainage Design Computer System, Volumes 1-6, FHWA-RD-88-120, FHWA. 1987.

Ginsberg, A. HY8 — Culvert Analysis Microcomputer Program, Applications Guide, FHWA-EPD-87-101, and software available from McTrans Center, 512 Weil Hall, University of Florida, Gainesville, Florida

Task Force on Hydrology and Hydraulics, Subcommittee on Design, American Association of State Highway and Transportation Officials. Guidelines for the Hydraulic Design of Culverts, 341 National Press Bldg., Washington, D.C. 20045. 1975.

Bodhaine, G.L. Measurement of Peak Discharge at Culverts by Indirect Methods, Techniques of Water-Resources Investigations of the USGS, Chapter A3. 1982.

Reihsen, G., and L.J. Harrison. Debris Control Structures, HEC No. 9, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590. August 1971.

Jens, S.W. Design of Urban Highway Drainage - The State of the Art, FHWA-TS-79-225, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590. August 1979.

Bureau of Reclamation. Design of Small Canal Structures, Denver, Co. 1974.

Culvert Design System. FHWA-TS-80-245, Hydraulics Section, Wyoming Highway Department, Cheyenne, Wyoming 82001. December 1980.

Design Charts For Open Channel Flow. HDS No. 3, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590. 1973.

Bradley, J.N. Hydraulics of Bridge Waterways, HDS No. 1, Second Edition, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590. September 1973.

Shearman, J.O., W.H. Kirby, V.R. Schneider, and H.N. Flippo. Bridge Waterways Analysis Model, FHWA-RD-86-108, FHWA, Washington, D.C.

King, H.W., and E.F. Brater. Handbook of Hydraulics, Sixth Edition, McGraw-Hill Book Co. 1976.

Appendix 8.A Design Charts

Culverts constructed in accordance with ADOT Standard Drawings should use the following charts.

Concrete Pipe -- Inlet Control Chart 1
- Groove end with headwall -Line 2
- Groove end Projecting -Line 3

Corrugated Metal Pipe Chart – Inlet Control Chart 2
- Mitered to conform to slope -Line 2
- End projecting -Line 3

Corrugated Metal Pipe Chart – Inlet Control Chart 3
- Beveled with Headwall -Line B

Concrete Box Culvert Chart – Inlet Control Chart 9
- Beveled with Headwall -Line 2

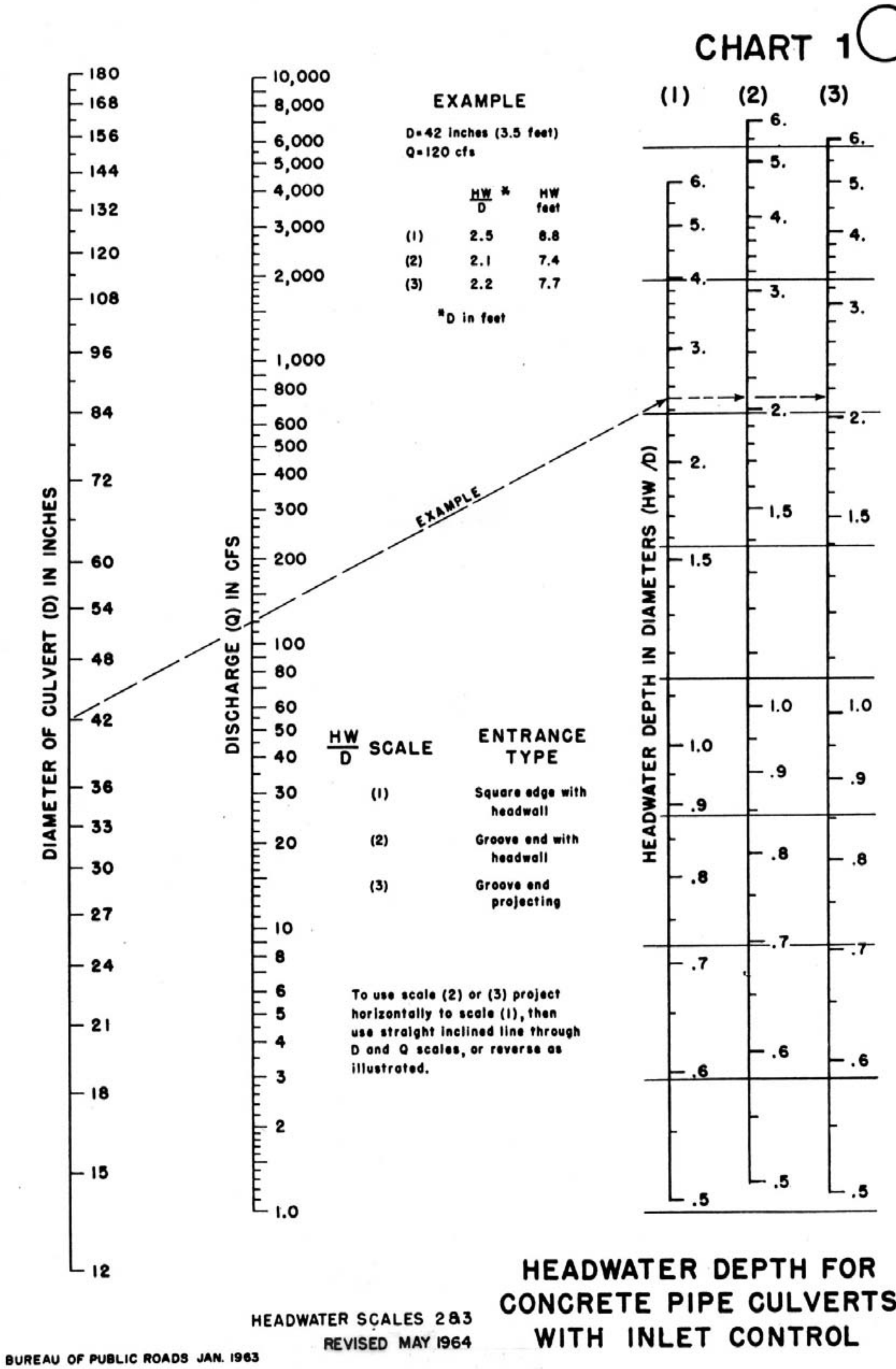


CHART 1
180
168
156
144
132
120
108
96
84
72
60
54
48
42
36
33
30
27
24
21
18
15
12
DIAMETER OF CULVERT (D) IN INCHES
10,000
8,000
6,000
5,000
4,000
3,000
2,000
1,000
800
600
500
400
300
200
100
80
60
50
40
30
20
10
8
6
5
4
3
2
1.0
DISCHARGE (Q) IN CFS
EXAMPLE
D=42 inches (3.5 feet)
Q=120 cfs
HW/D *
HW feet
(1) 2.5 8.8
(2) 2.1 7.4
(3) 2.2 7.7
*D in feet
EXAMPLE
HW/D SCALE
ENTRANCE TYPE
(1) Square edge with headwall
(2) Groove end with headwall
(3) Groove end projecting
To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.
(1)
(2)
(3)
HEADWATER DEPTH IN DIAMETERS (HW/D)
6.
5.
4.
3.
2.
1.5
1.0
.9
.8
.7
.6
.5
HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL
HEADWATER SCALES 2&3
REVISED MAY 1964
BUREAU OF PUBLIC ROADS JAN. 1963

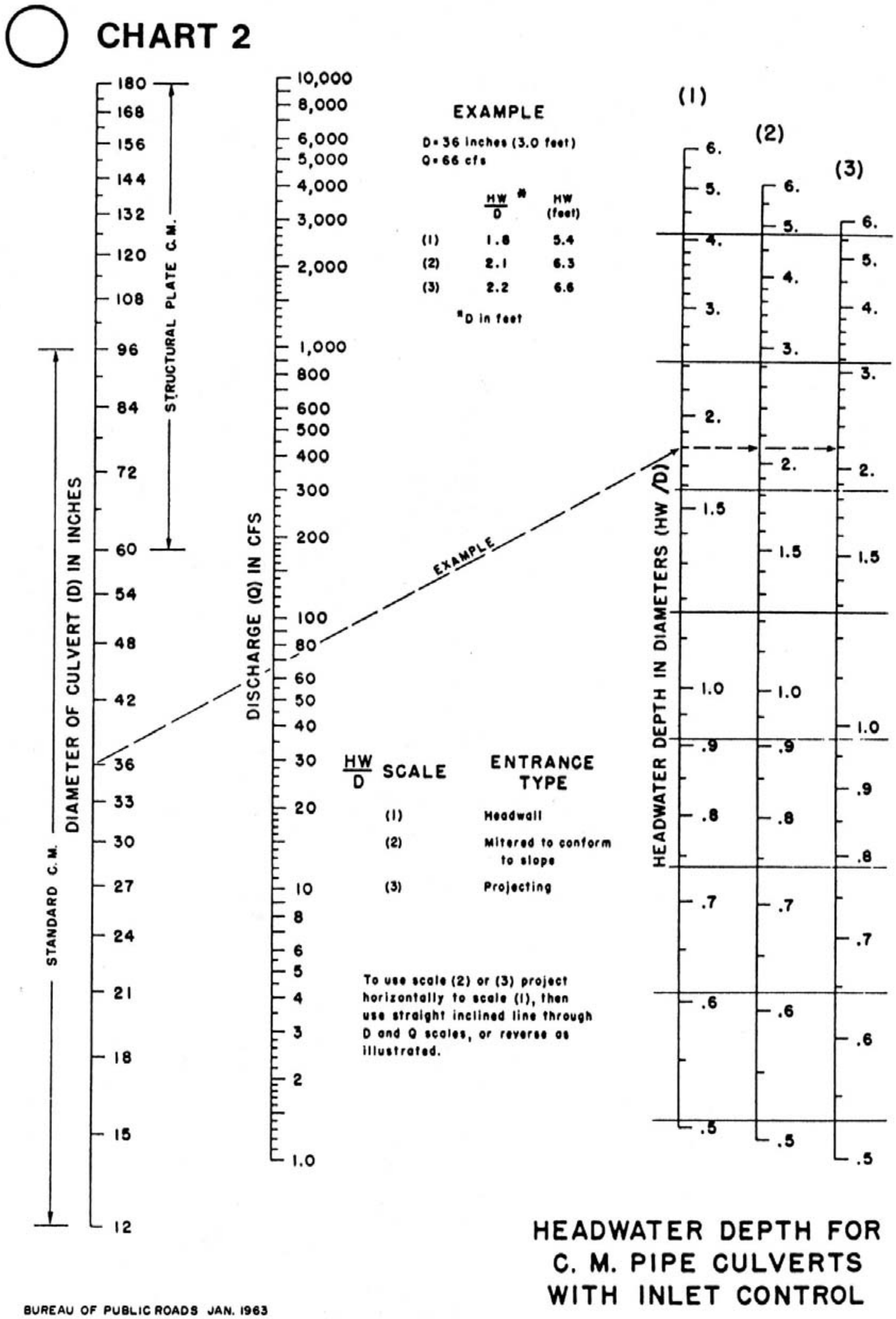
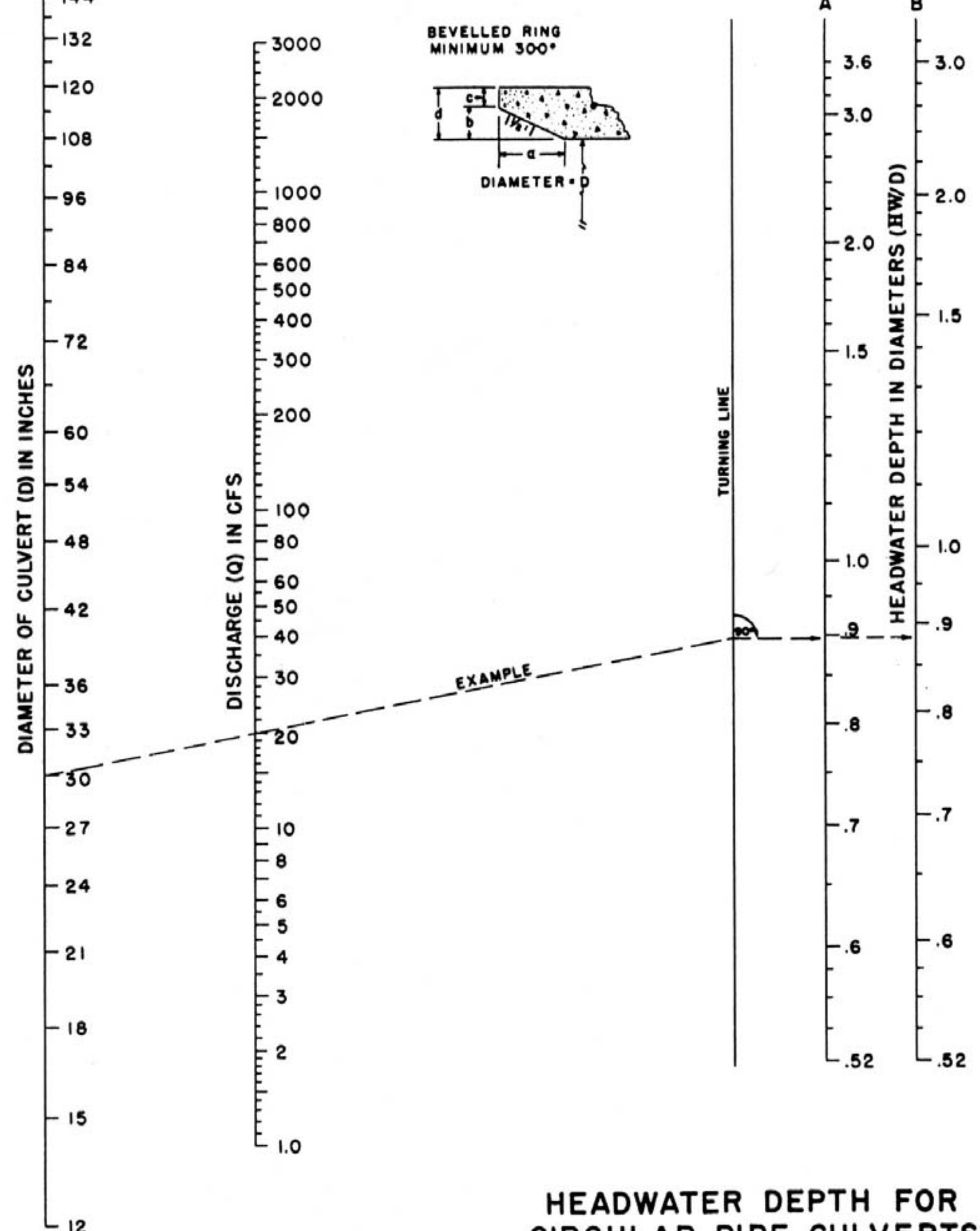


CHART 2
180
168
156
144
132
120
108
96
84
72
60
54
48
42
36
33
30
27
24
21
18
15
12
STRUCTURAL PLATE C.M.
STANDARD C.M.
DIAMETER OF CULVERT (D) IN INCHES
10,000
8,000
6,000
5,000
4,000
3,000
2,000
1,000
800
600
500
400
300
200
100
80
60
50
40
30
20
10
8
6
5
4
3
2
1.0
DISCHARGE (Q) IN CFS
EXAMPLE
D = 36 inches (3.0 feet)
Q = 66 cfs
HW/D * HW (feet)
(1) 1.8 5.4
(2) 2.1 6.3
(3) 2.2 6.6
*D in feet
EXAMPLE
HW/D SCALE
ENTRANCE TYPE
(1) Headwall
(2) Mitered to conform to slope
(3) Projecting
To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.
(1)
(2)
(3)
6.
5.
4.
3.
2.
1.5
1.0
.9
.8
.7
.6
.5
HEADWATER DEPTH IN DIAMETERS (HW/D)
HEADWATER DEPTH FOR
C. M. PIPE CULVERTS
WITH INLET CONTROL
BUREAU OF PUBLIC ROADS JAN. 1963

CHART 3

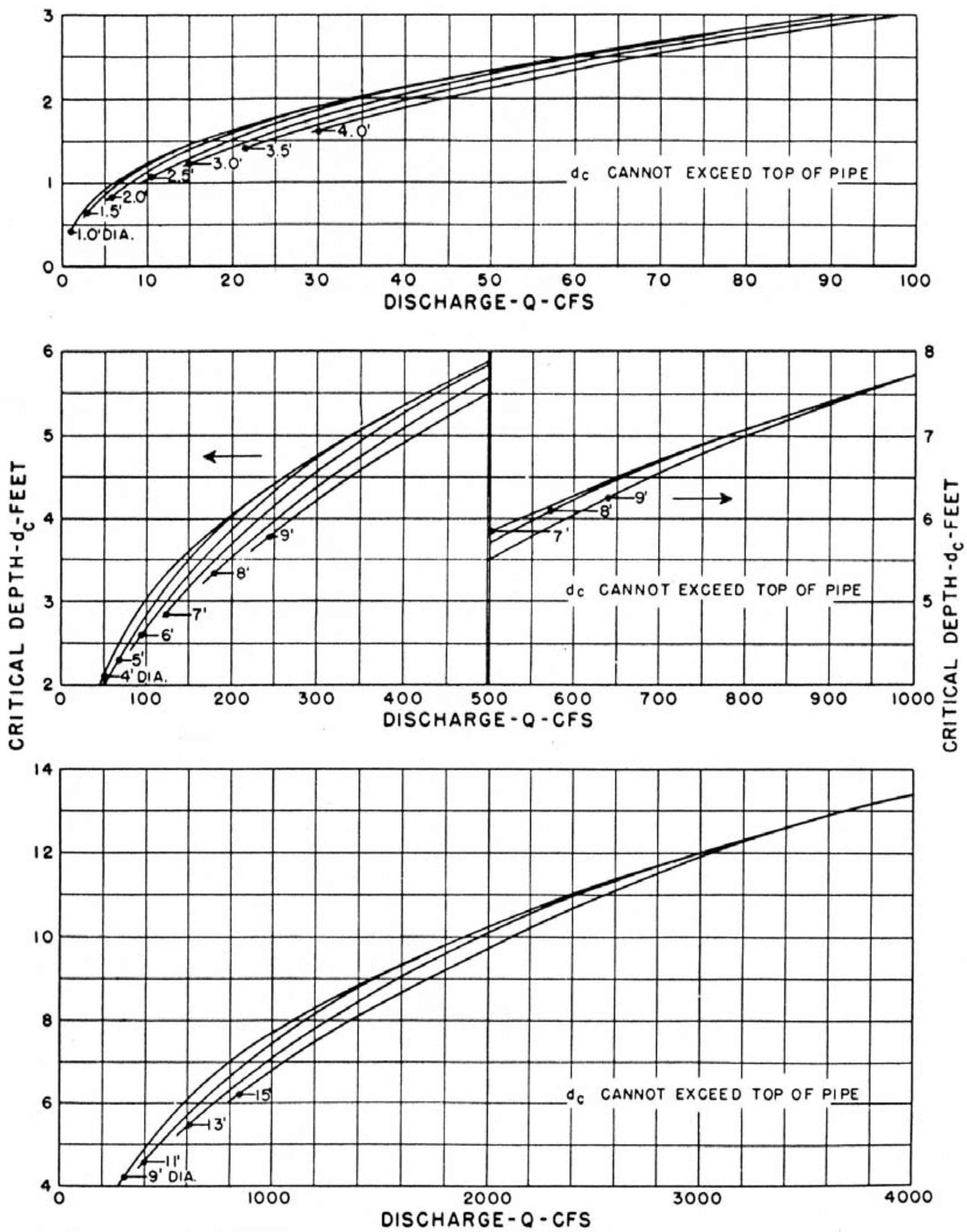
$\frac{b}{D}$	$\frac{a}{D}$	$\frac{c}{D}$	$\frac{d}{D}$	ENTRANCE TYPE
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B



)ERAL HIGHWAY ADMINISTRATION
MAY 1973

HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL

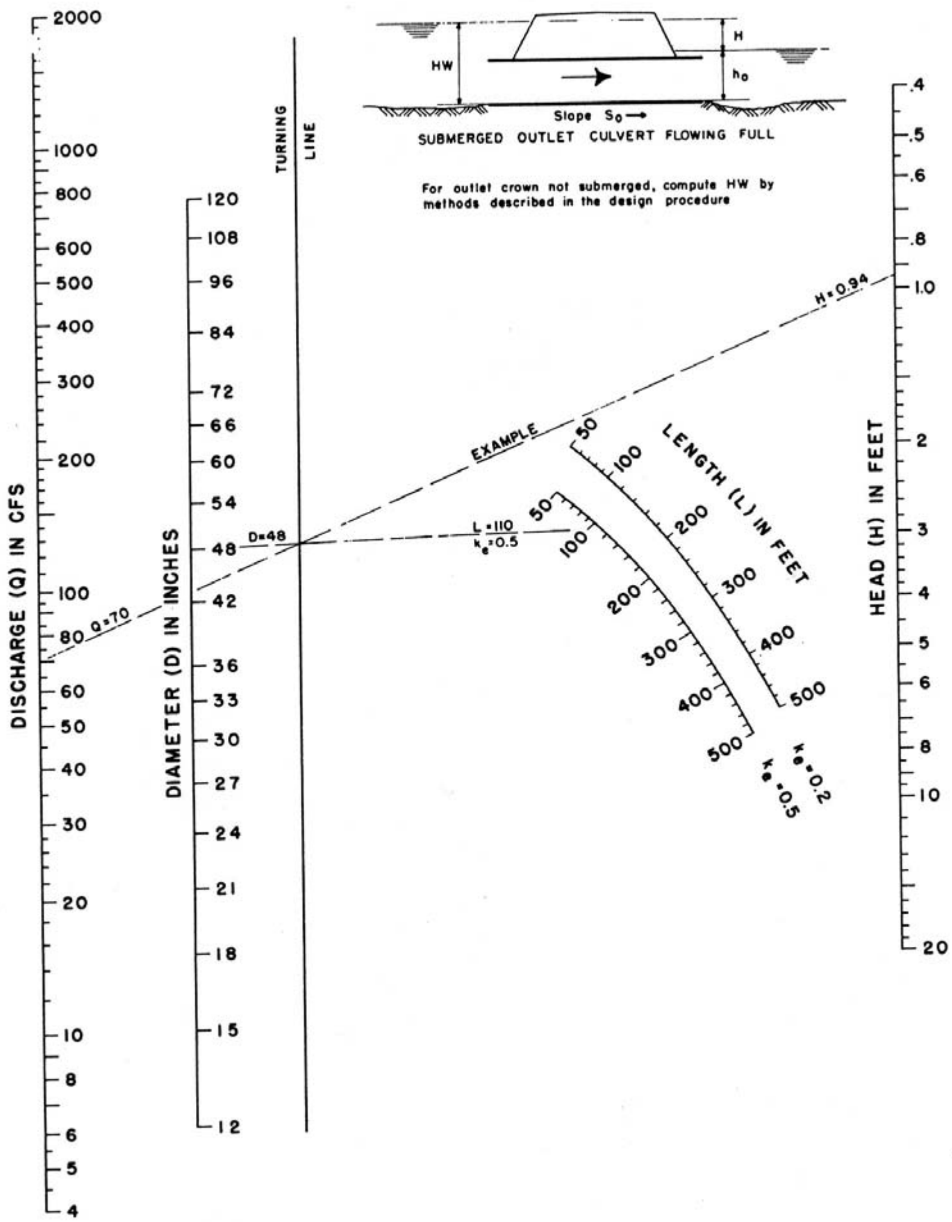
CHART 4



BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
CIRCULAR PIPE

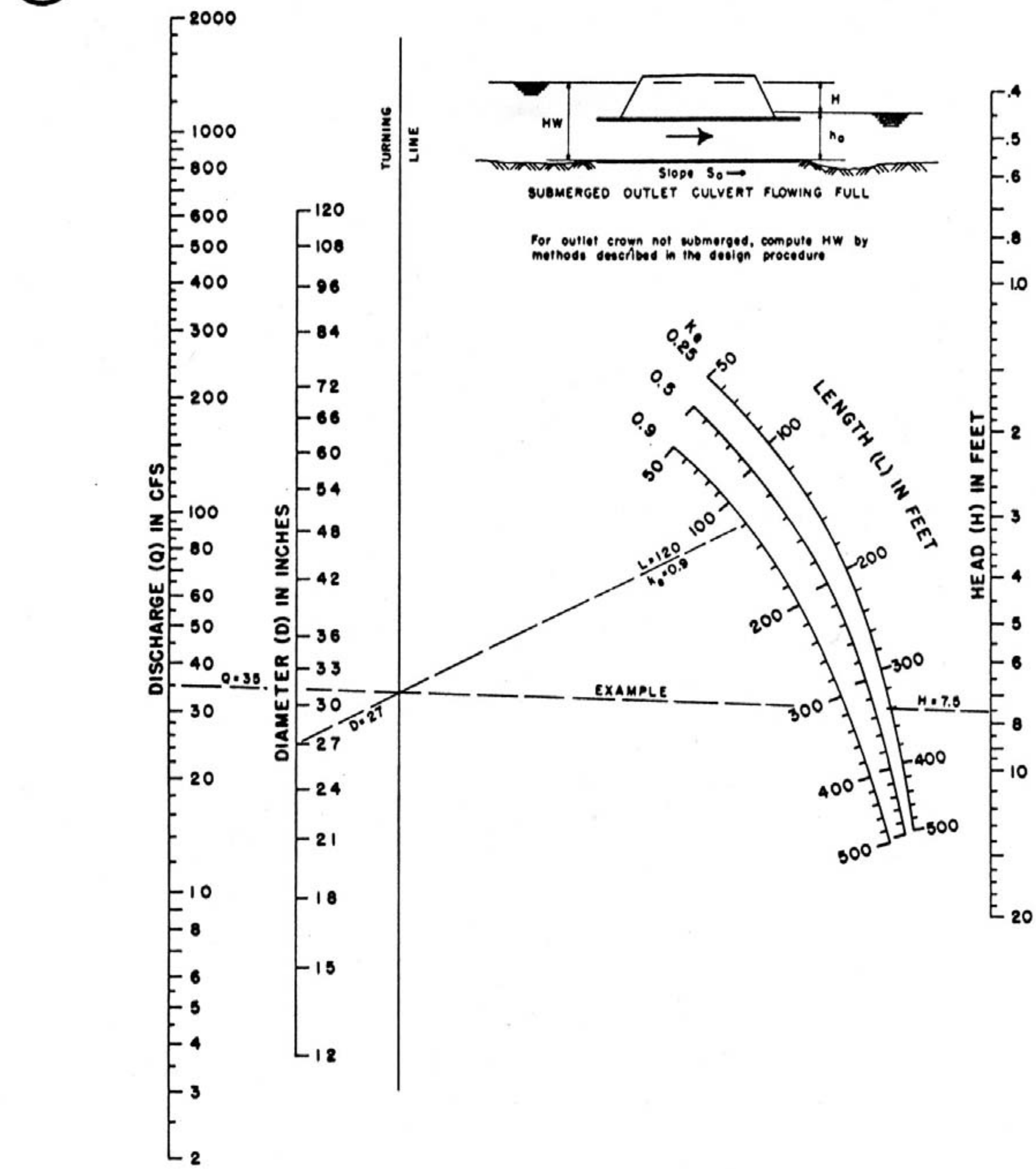
CHART 5



HEAD FOR
CONCRETE PIPE CULVERTS
FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 6



HEAD FOR STANDARD C. M. PIPE CULVERTS FLOWING FULL
n = 0.024

BUREAU OF PUBLIC ROADS JAN. 1963

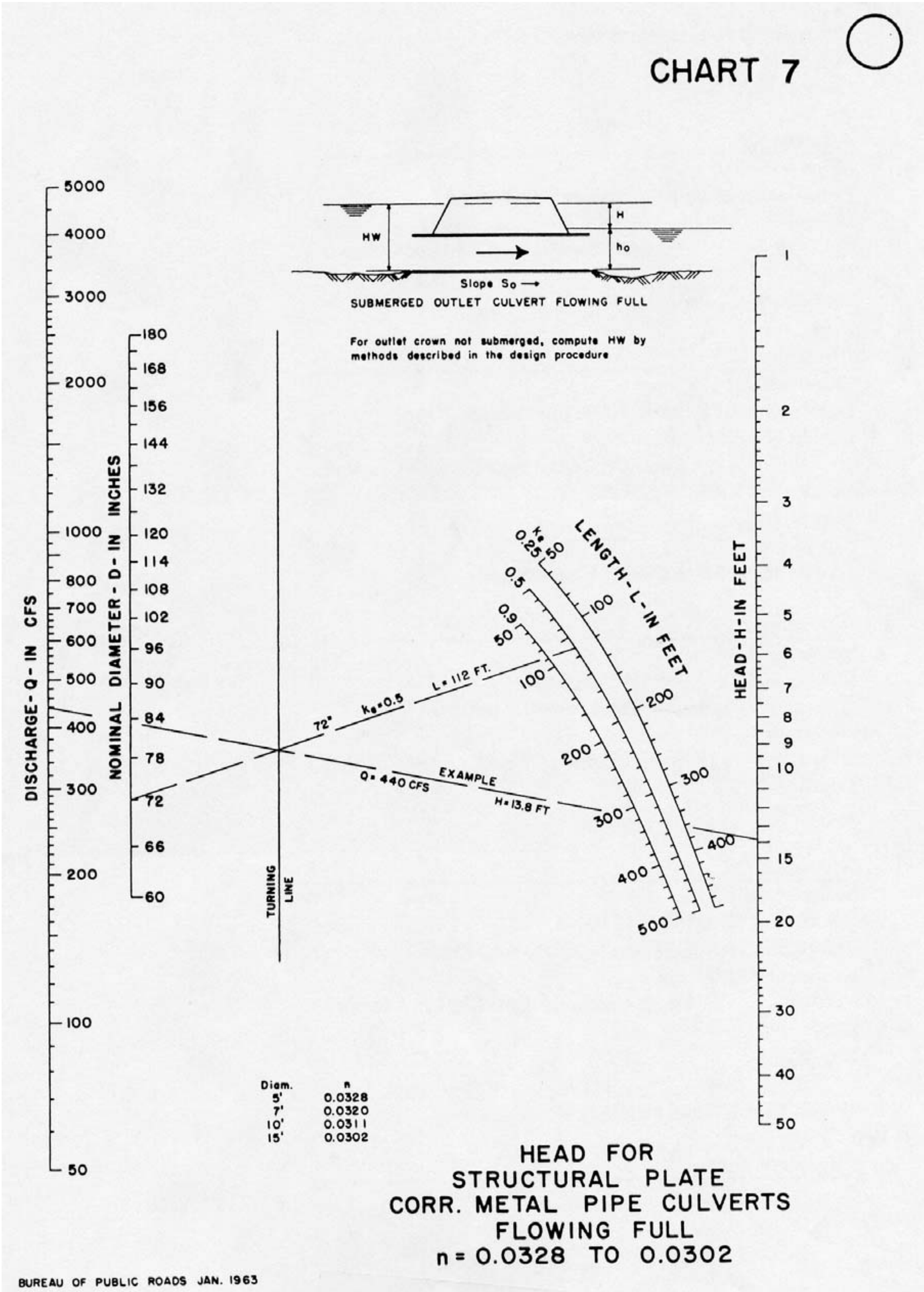


CHART 7
HW
H
ho
Slope So
SUBMERGED OUTLET CULVERT FLOWING FULL
For outlet crown not submerged, compute HW by methods described in the design procedure
DISCHARGE - Q - IN CFS
5000
4000
3000
2000
1000
800
700
600
500
400
300
200
100
50
NOMINAL DIAMETER - D - IN INCHES
180
168
156
144
132
120
114
108
102
96
90
84
78
72
66
60
TURNING LINE
72"
k_e=0.5
L = 112 FT.
Q = 440 CFS
EXAMPLE
H = 13.8 FT
LENGTH - L - IN FEET
k_e
0.25
0.5
0.9
HEAD - H - IN FEET
Diam. n
5' 0.0328
7' 0.0320
10' 0.0311
15' 0.0302
HEAD FOR
STRUCTURAL PLATE
CORR. METAL PIPE CULVERTS
FLOWING FULL
n = 0.0328 TO 0.0302
BUREAU OF PUBLIC ROADS JAN. 1963

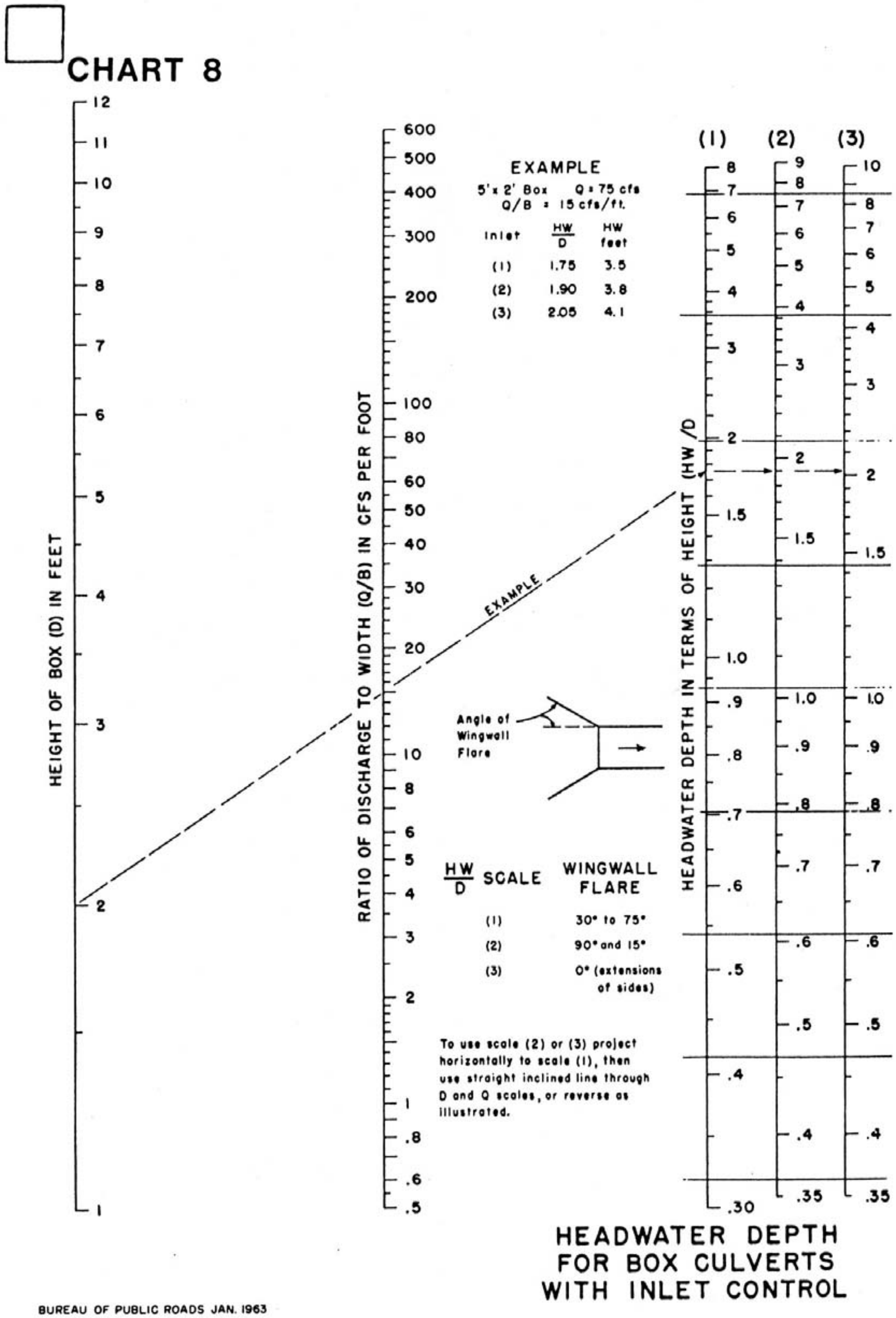


CHART 8
HEIGHT OF BOX (D) IN FEET
RATIO OF DISCHARGE TO WIDTH (Q/B) IN CFS PER FOOT
HEADWATER DEPTH IN TERMS OF HEIGHT (HW/D)
(1) (2) (3)
EXAMPLE
5' x 2' Box Q = 75 cfs
Q/B = 15 cfs/ft.
Inlet HW/D HW feet
(1) 1.75 3.5
(2) 1.90 3.8
(3) 2.05 4.1
EXAMPLE
Angle of Wingwall Flare
HW/D SCALE WINGWALL FLARE
(1) 30° to 75°
(2) 90° and 15°
(3) 0° (extensions of sides)
To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.
HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL
BUREAU OF PUBLIC ROADS JAN. 1963

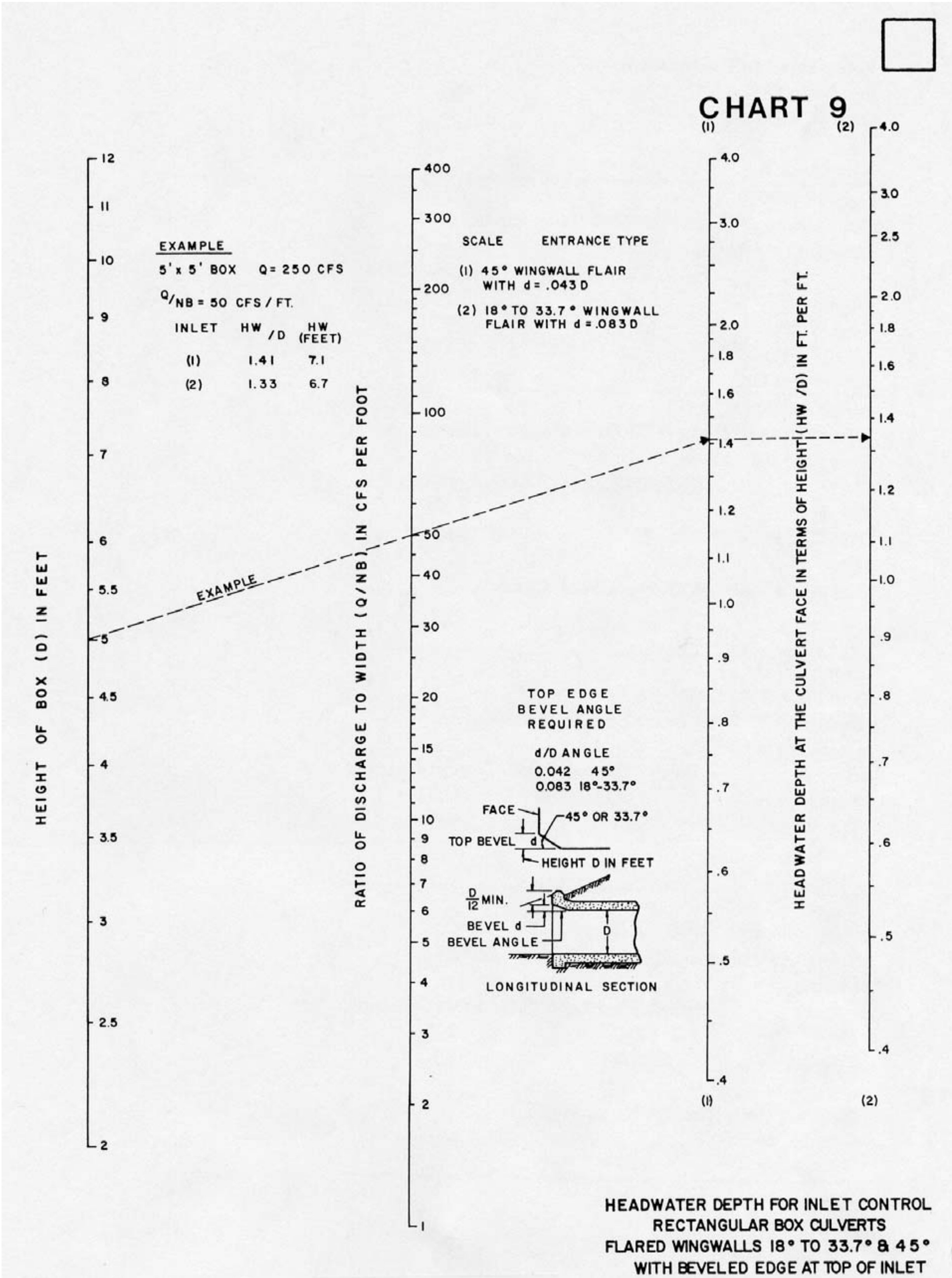
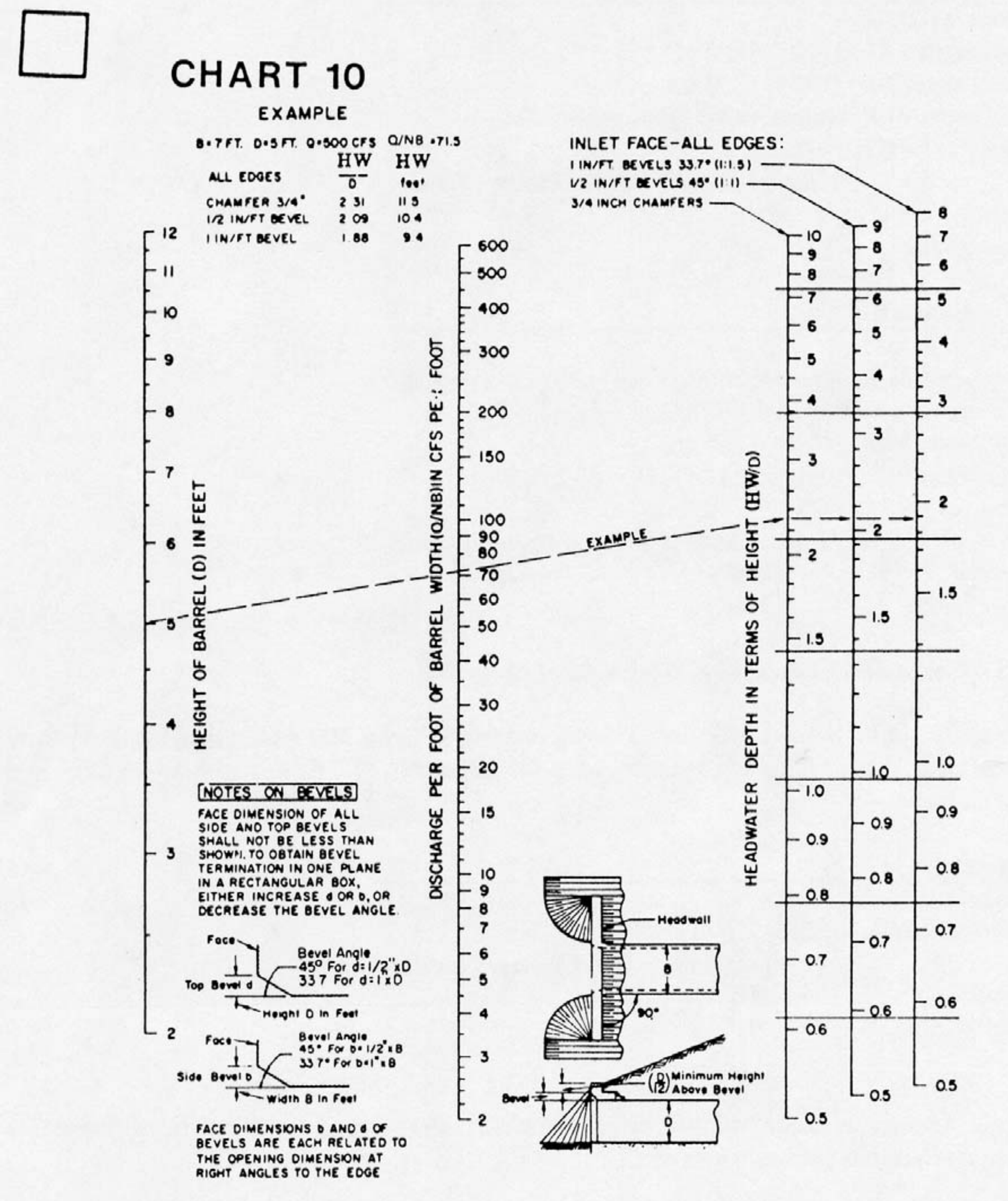
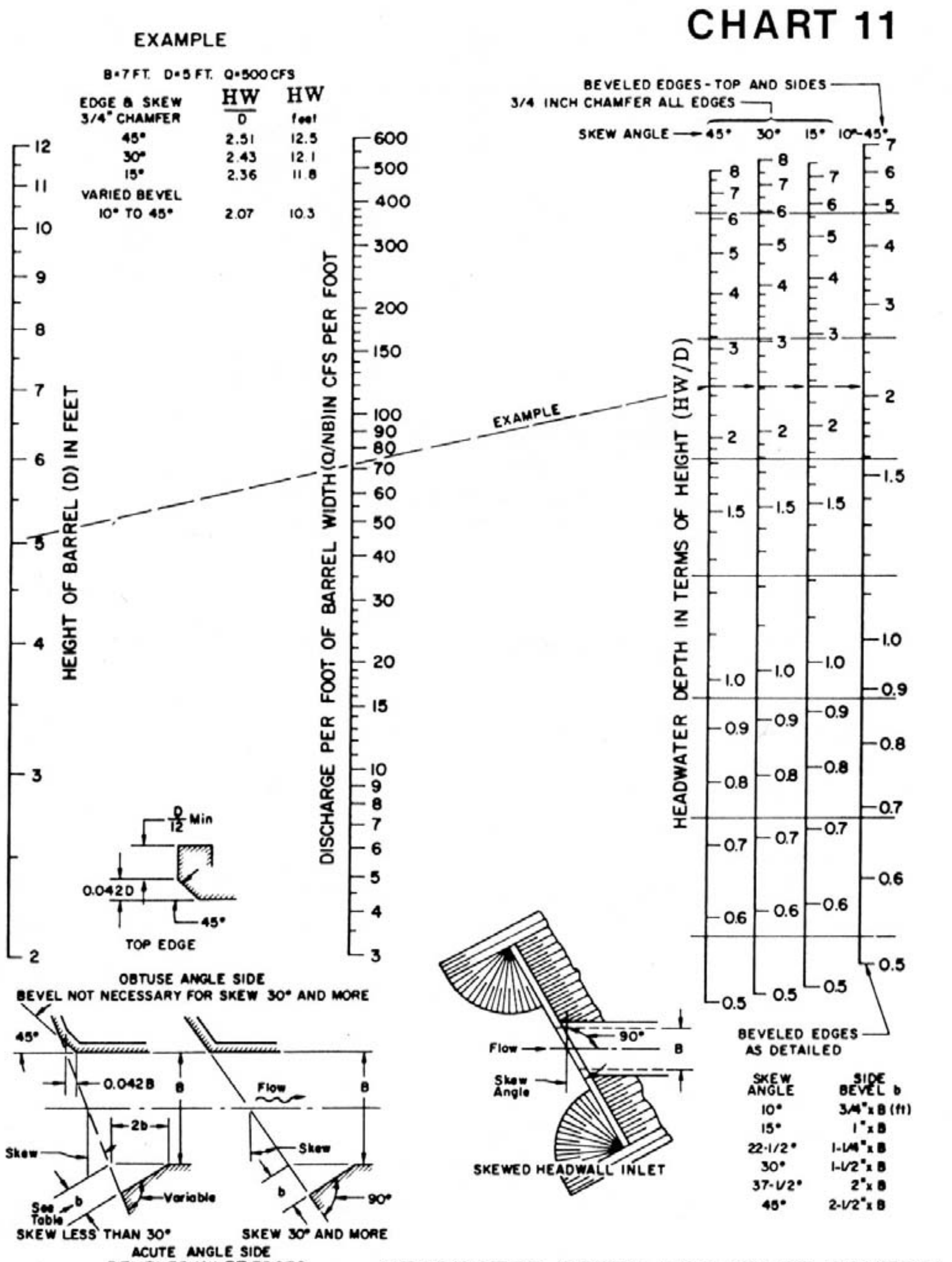


CHART 9
EXAMPLE
5' x 5' BOX Q = 250 CFS
Q/NB = 50 CFS / FT.
INLET HW/D HW (FEET)
(1) 1.41 7.1
(2) 1.33 6.7
SCALE ENTRANCE TYPE
(1) 45° WINGWALL FLAIR WITH d = .043 D
(2) 18° TO 33.7° WINGWALL FLAIR WITH d = .083 D
HEIGHT OF BOX (D) IN FEET
RATIO OF DISCHARGE TO WIDTH (Q/NB) IN CFS PER FOOT
HEADWATER DEPTH AT THE CULVERT FACE IN TERMS OF HEIGHT (HW /D) IN FT. PER FT.
EXAMPLE
TOP EDGE BEVEL ANGLE REQUIRED
d/D ANGLE
0.042 45°
0.083 18°-33.7°
FACE
45° OR 33.7°
TOP BEVEL d
HEIGHT D IN FEET
D/12 MIN.
BEVEL d
BEVEL ANGLE
D
LONGITUDINAL SECTION
(1)
(2)
HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS 18° TO 33.7° & 45°
WITH BEVELED EDGE AT TOP OF INLET



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
90° HEADWALL
CHAMFERED OR BEVELED INLET EDGES

FEDERAL HIGHWAY ADMINISTRATION
MAY 1973



HEADWATER DEPTH FOR INLET CONTROL
SINGLE BARREL BOX CULVERTS
SKEWED HEADWALLS
CHAMFERED OR BEVELED INLET EDGES

FEDERAL HIGHWAY ADMINISTRATION
MAY 1973

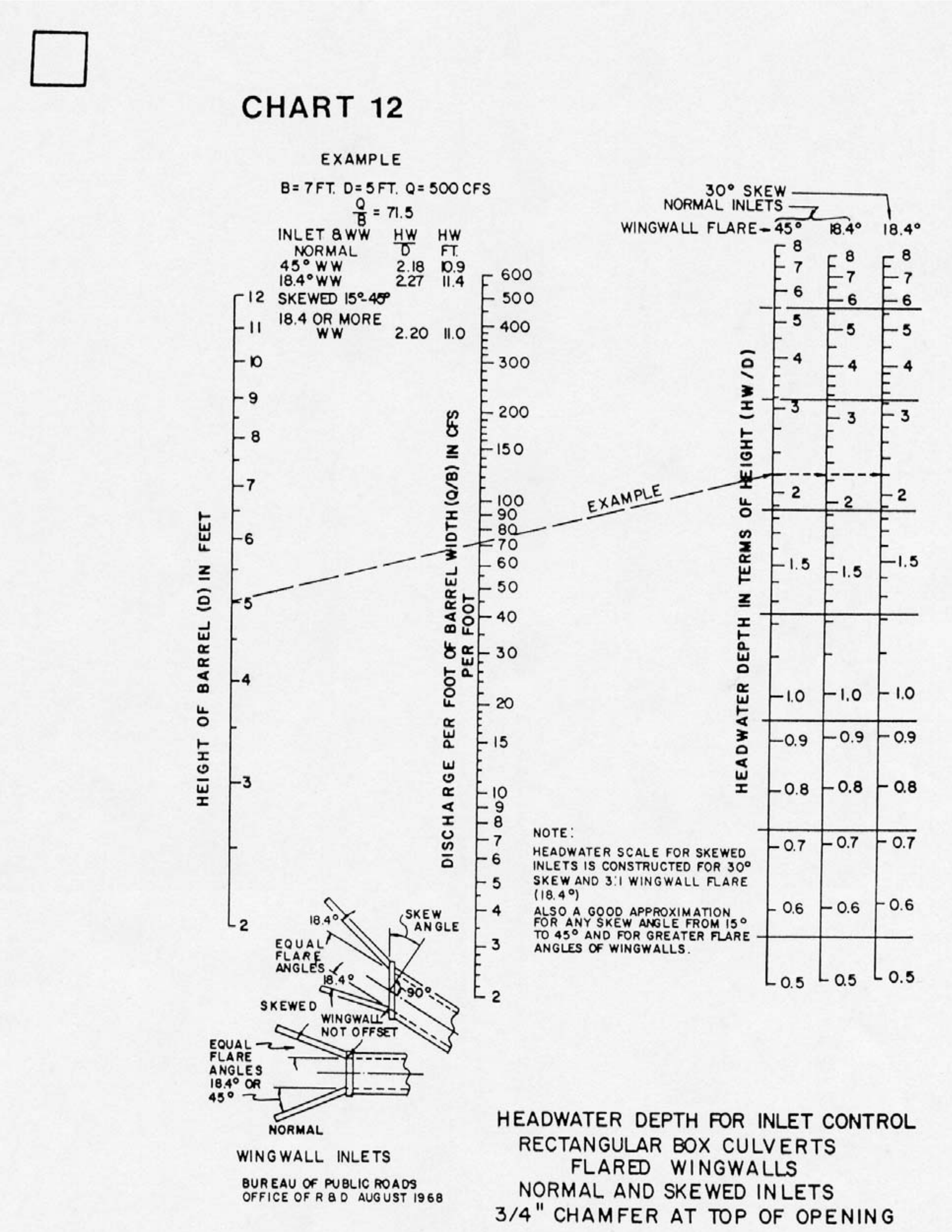


CHART 12
EXAMPLE
B= 7 FT. D= 5 FT. Q= 500 CFS
Q/B = 71.5
INLET & WW | HW/D | HW FT.
NORMAL
45° WW 2.18 10.9
18.4° WW 2.27 11.4
SKEWED 15°-45°
18.4 OR MORE WW 2.20 11.0
HEIGHT OF BARREL (D) IN FEET
DISCHARGE PER FOOT OF BARREL WIDTH (Q/B) IN CFS PER FOOT
HEADWATER DEPTH IN TERMS OF HEIGHT (HW/D)
30° SKEW
NORMAL INLETS
WINGWALL FLARE 45° 18.4° 18.4°
EXAMPLE
NOTE:
HEADWATER SCALE FOR SKEWED INLETS IS CONSTRUCTED FOR 30° SKEW AND 3:1 WINGWALL FLARE (18.4°)
ALSO A GOOD APPROXIMATION FOR ANY SKEW ANGLE FROM 15° TO 45° AND FOR GREATER FLARE ANGLES OF WINGWALLS.
18.4°
SKEW ANGLE
EQUAL FLARE ANGLES
18.4°
90°
SKEWED
WINGWALL NOT OFFSET
EQUAL FLARE ANGLES 18.4° OR 45°
NORMAL
WINGWALL INLETS
BUREAU OF PUBLIC ROADS
OFFICE OF R & D AUGUST 1968
HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS
NORMAL AND SKEWED INLETS
3/4" CHAMFER AT TOP OF OPENING

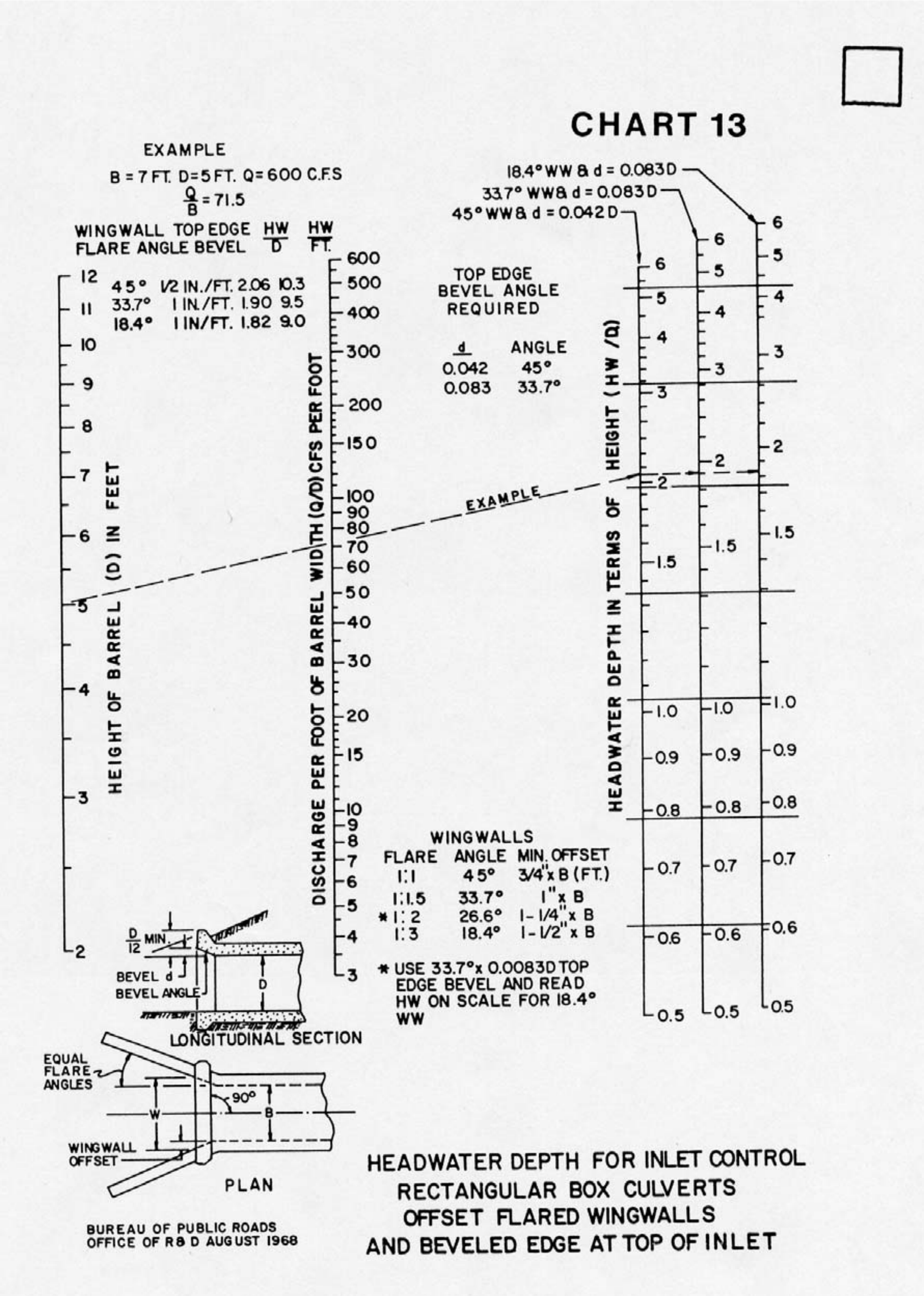
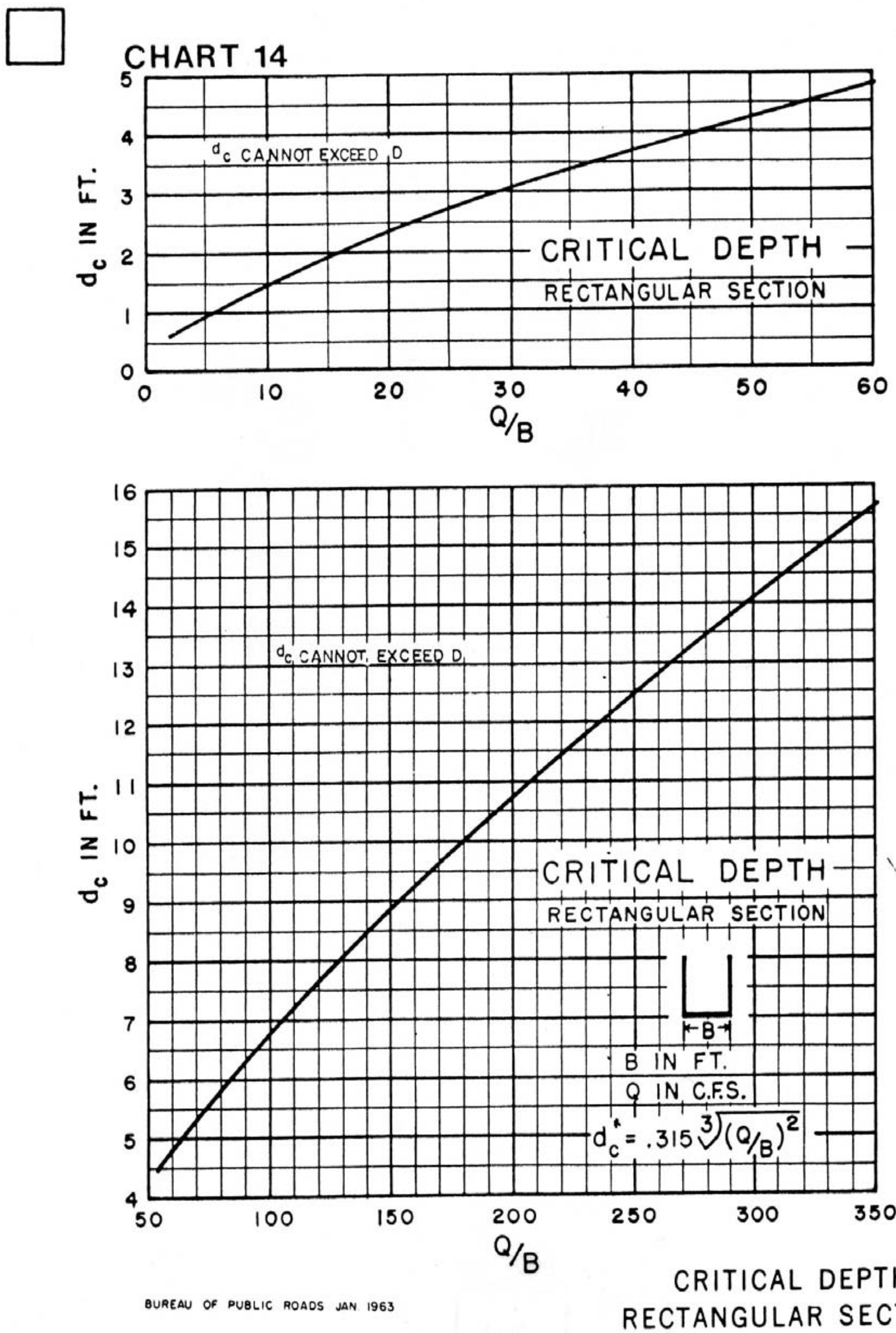
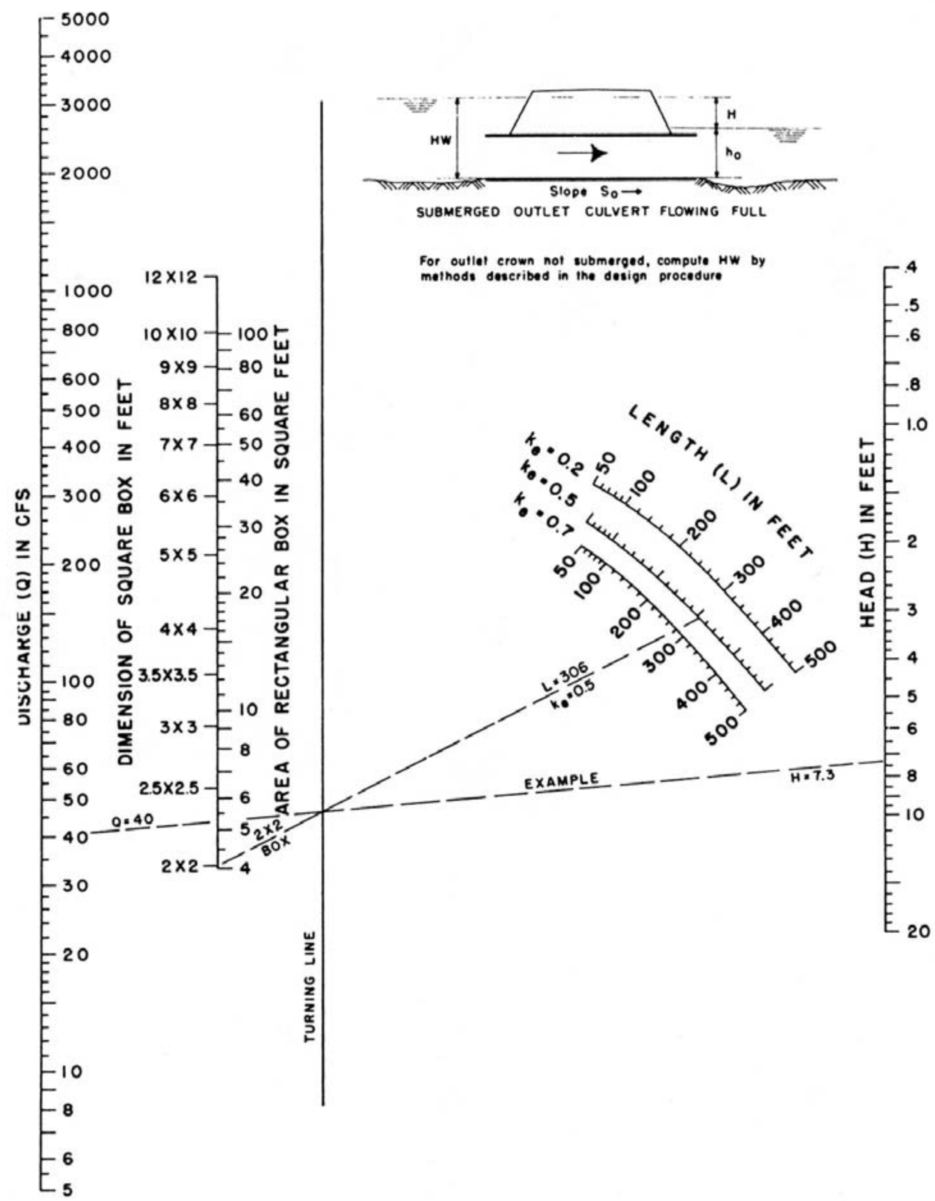


CHART 13
EXAMPLE
B = 7 FT. D=5 FT. Q= 600 C.F.S
Q/B = 71.5
WINGWALL FLARE ANGLE | TOP EDGE BEVEL | HW/D | HW FT.
45° 1/2 IN./FT. 2.06 10.3
33.7° 1 IN./FT. 1.90 9.5
18.4° 1 IN/FT. 1.82 9.0
HEIGHT OF BARREL (D) IN FEET
DISCHARGE PER FOOT OF BARREL WIDTH (Q/D) CFS PER FOOT
HEADWATER DEPTH IN TERMS OF HEIGHT (HW /D)
18.4° WW & d = 0.083D
33.7° WW& d = 0.083D
45° WW & d = 0.042D
TOP EDGE BEVEL ANGLE REQUIRED
d ANGLE
0.042 45°
0.083 33.7°
EXAMPLE
WINGWALLS
FLARE ANGLE MIN. OFFSET
1:1 45° 3/4"x B (FT.)
1:1.5 33.7° 1"x B
* 1:2 26.6° 1-1/4"x B
1:3 18.4° 1-1/2"x B
* USE 33.7°x 0.0083D TOP EDGE BEVEL AND READ HW ON SCALE FOR 18.4° WW
D/12 MIN.
BEVEL d
BEVEL ANGLE
LONGITUDINAL SECTION
EQUAL FLARE ANGLES
WINGWALL OFFSET
90°
W
B
PLAN
BUREAU OF PUBLIC ROADS OFFICE OF R& D AUGUST 1968
HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
OFFSET FLARED WINGWALLS
AND BEVELED EDGE AT TOP OF INLET



CRITICAL DEPTH
RECTANGULAR SECTION

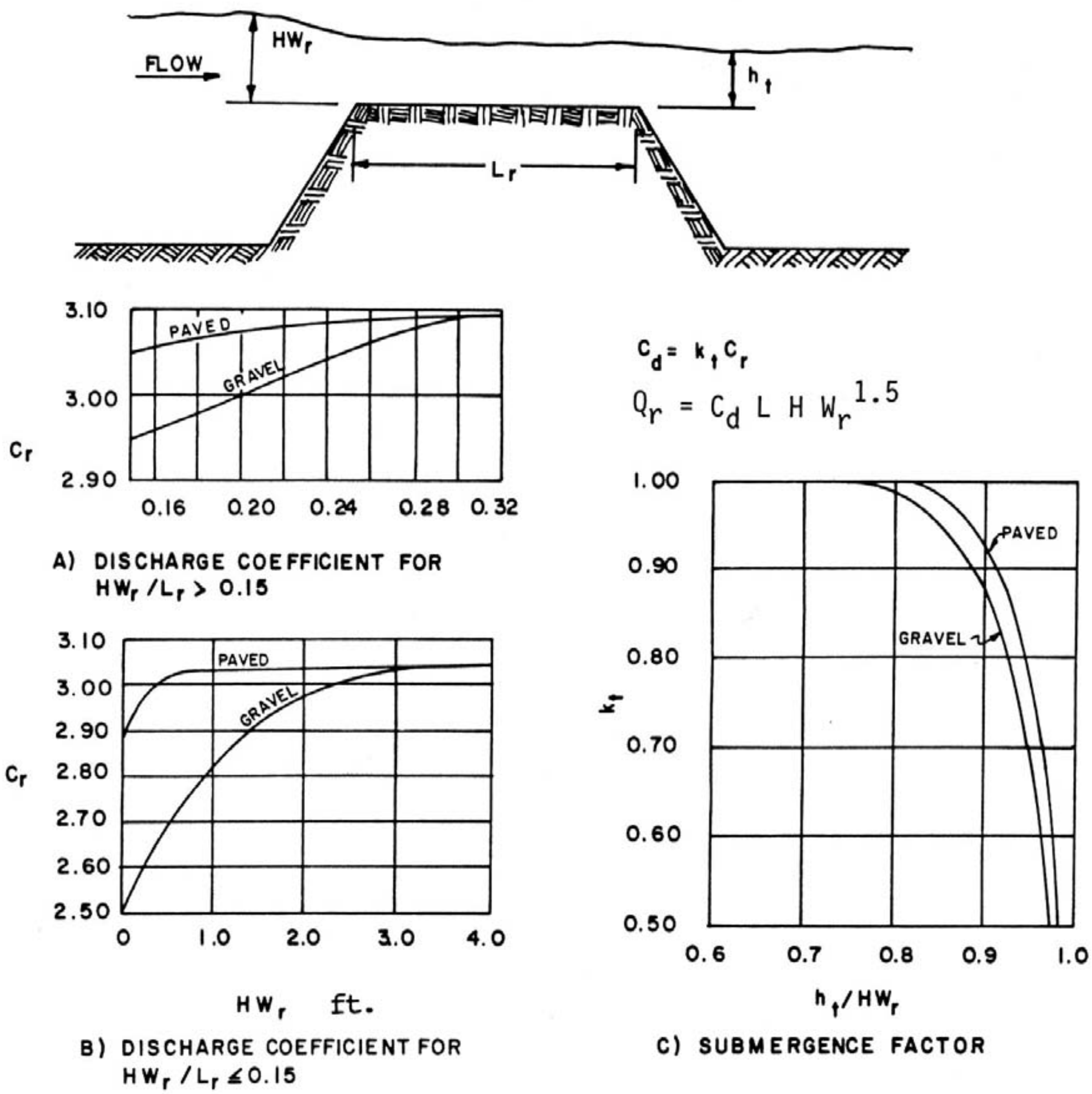
CHART 15



HEAD FOR
CONCRETE BOX CULVERTS
FLOWING FULL
n = 0.012

AU OF PUBLIC ROADS JAN. 1963

CHART 16



DISCHARGE COEFFICIENTS
FOR ROADWAY OVERTOPPING

Appendix 8.B Tables and Forms

Table 1 RECOMMENDED MANNING'S n VALUES*

Type of Conduit	Wall Description	Manning's n
Concrete Pipe	Smooth walls	0.010-0.013
Concrete Boxes	Smooth walls	0.012-0.015
Corrugated Metal Pipes and Boxes, Annular or Helical Pipe (n varies barrel size) See HDS5	2 2/3 by 1/2 inch corrugations	0.022-0.027
	6 by 1 inch corrugations	0.022-0.025
	5 by 1 inch corrugations	0.025-0.026
	3 by 1 inch corrugations	0.027-0.028
	6 by 2 inch structural plate	0.033-0.035
	9 by 2 1/2 inch structural plate	0.033-0.037
Corrugated Metal Pipes, Helical Corrugations, Full Circular Flow	2 2/3 by 1/2 inch corrugations	0.012-0.024
Spiral Rib Metal	Smooth walls	0.012-0.013

*Note 1: The values indicated in this table are recommended Manning's "n" design values. Actual field values for older existing pipelines may vary depending on the effects of abrasion, corrosion, deflection and joint conditions. Concrete pipe with poor joints and deteriorated walls may have "n" values of 0.014 to 0.018. Corrugated metal pipe with joint and wall problems may also have higher "n" values, and in addition, may experience shape changes which could adversely effect the general hydraulic characteristics of the culvert.

Note 2: For further information concerning Manning n values for selected conduits consult Hydraulic Design of Highway Culverts, Federal Highway Administration, HDS No. 5, page 163.

TABLE 2 - ENTRANCE LOSS COEFFICIENTS

Outlet Control, Full or Partly Full

$$H_e = k_e \left[\frac{V^2}{2g} \right]$$

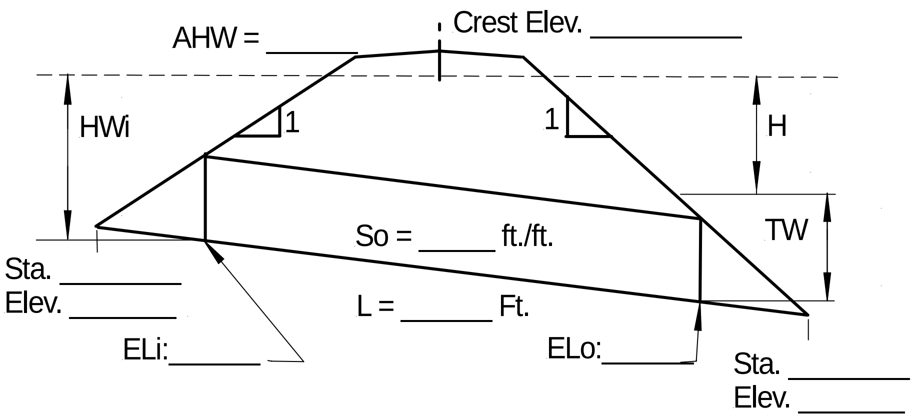
Type of Structure and Design of Entrance	Coefficient k_e
Pipe, Concrete	
Mitered to conform to fill slope	0.7
*End-Section conforming to fill slope	0.5
Projecting from fill, sq. cut end	0.5
Headwall or headwall and wingwalls	
Square-edge	0.5
Rounded (radius = 1/12D)	0.2
Socket end of pipe (groove-end)	0.2
Projecting from fill, socket end (groove-end)	0.2
Beveled edges, 33.7° or 45° bevels	0.2
Side-or slope-tapered inlet	0.2
Pipe, or Pipe-Arch, Corrugated Metal	
Projecting from fill (no headwall)	0.9
Mitered to conform to fill slope, paved or unpaved slope	0.7
Headwall or headwall and wingwalls square-edge	0.5
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side-or slope-tapered inlet	0.2
Box, Reinforced Concrete	
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Wingwalls at 10° to 25° or 30° to 75° to barrel	
Square-edged at crown	0.5
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of 1/12 barrel dimension, or beveled edges on 3 sides	0.2
Wingwalls at 30° to 75° to barrel	
Crown edge rounded to radius of 1/12 barrel dimension, or beveled top edge	0.2
Side-or slope-tapered inlet	0.2

*Note: "End Section conforming to fill slope," made of either metal or concrete, are the sections commonly available from manufacturers. From limited hydraulic tests they are equivalent in operation to a headwall in both <u>inlet</u> and <u>outlet</u> control. Some end sections, incorporating a <u>closed</u> taper in their design have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.

Project Name ________________________________ Proj. No. ______________

Station/Location ________________________________ Designer__________ Date__________

Subject ________________________________ Checker__________ Date__________



Design Flows:

R.I (Years)	Flow (cfs)	T.W. (ft)

For Table: $EL_{hi} = EL_i + Hw_i$

h_o = greater of TW or $(d_c+D)/2$

H from chart 15

$El_{ho} = El_o + h_o + H$

Culvert Form

Culvert Description:																
Total Flow (cfs)	Flow/Ft: (cfs)	HEADWATER CALCULATIONS												Control HW:	Vo: Ft/sec	Comments
		Inlet Control: Chart ___				Outlet Control: Chart ___										
		Hw_i/D	Hw_i	Fall	EL_{hi}	TW	d_c	$(d_c+D)/2$:	h_o	k_e	H	EL_{ho}				

Appendix 8.C Tapered Inlets

8.C.1 General

A tapered inlet is a flared culvert inlet with an enlarged face section and a hydraulically efficient throat section. A tapered inlet may have a depression, or FALL, incorporated into the inlet structure or located upstream of the inlet. The depression is used to exert more head on the throat section for a given headwater elevation. Therefore, tapered inlets improve culvert performance by providing a more efficient control section (the throat). Tapered inlets with FALL also improve performance by increasing the head on the throat.

- Tapered inlets are recommended for use on culverts flowing in inlet control. This will maximize the benefit of opening the entrance to reduce the headwater.
- Tapered inlets are not recommended for use on culverts flowing in outlet control because the simple beveled edge is of equal benefit.
- Design criteria and methods have been developed for two basic tapered inlet designs: the side-tapered inlet and the slope-tapered inlet.
- Tapered inlet design charts are available for rectangular box culverts and circular pipe culverts.

8.C.2 Side-tapered

The side-tapered inlet has an enlarged face section with the transition to the culvert barrel accomplished by tapering the sidewalls (Figure 8.C.1). The face section is about the same height as the barrel height and the inlet floor is an extension of the barrel floor. The inlet roof may slope upward slightly, provided that the face height does not exceed the barrel height by more than 10 percent (1.1D). The intersection of the tapered sidewalls and the barrel is defined as the throat section.

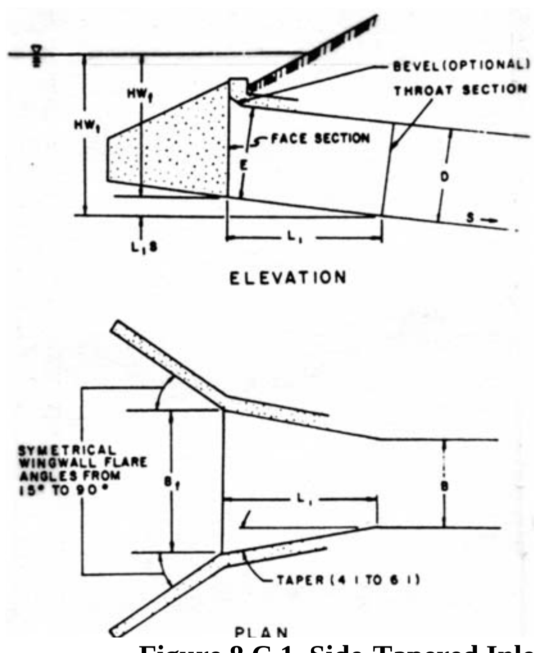


Figure 8.C.1 Side-Tapered Inlet

Appendix 8.C Tapered Inlets (continued)

8.C.2 Side-tapered (continued)

There are two possible control sections, the face and the throat. H_f, shown in Figure 8.A.2, is the headwater depth measured from the face section invert and H_t is the headwater depth measured from the throat section invert. The throat of a side-tapered inlet is a very efficient control section. The flow contraction is nearly eliminated at the throat. In addition, the throat is always slightly lower than the face so that more head is exerted on the throat for a given headwater elevation.

The beneficial effect of depressing the throat section below the streambed can be increased by installing a depression upstream of the side-tapered inlet. Figure 8.C.2 depicts a side-tapered inlet with the depression contained between wingwalls. For this type of depression, the floor of the barrel should extend upstream from the face a minimum distance of D/2 before sloping upward more steeply. The length of the resultant upstream crest where the slope of the depression meets the streambed should be checked to assure that the crest will not control the flow at the design flow and headwater. If the crest length is too short, the crest may act as a weir control section

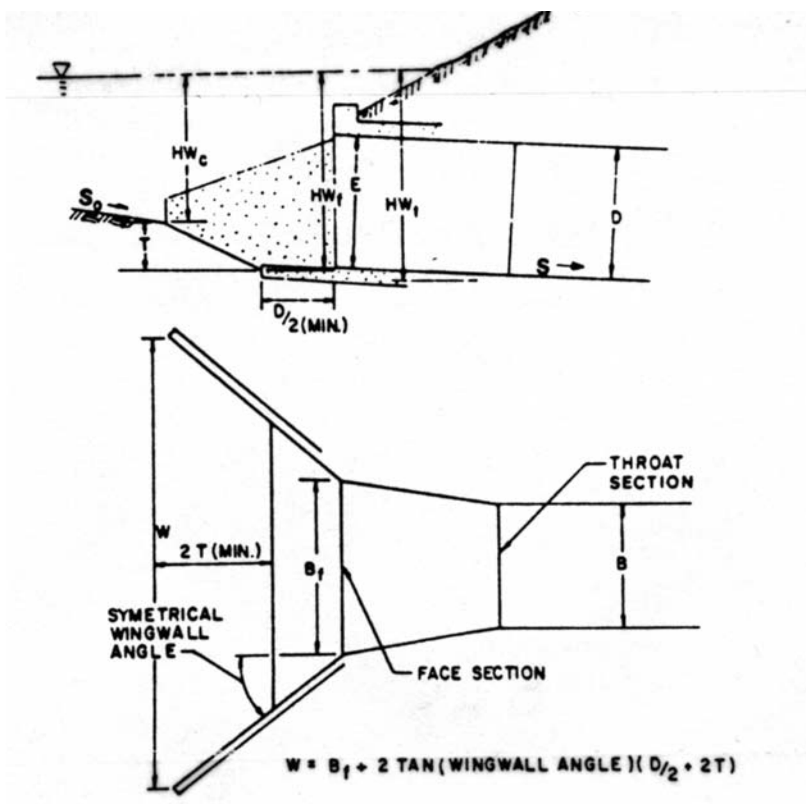


Figure 8.C.2 Side-tapered Inlet With Upstream Depression Contained Between Wingwalls

Appendix 8.C Tapered Inlets (continued)

8.C.3 Slope-tapered Inlet

The slope-tapered inlet, like the side-tapered inlet, has an enlarged face section with tapered sidewalls meeting the culvert barrel walls at the throat section. (Figure 8.C.3) In addition, a vertical FALL is incorporated into the inlet between the face and throat sections. This FALL concentrates more head on the throat section. At the location where the steeper slope of the inlet intersects the flatter slope of the barrel, a third section, designated the bend section, is formed.

A slope-tapered inlet has three possible control sections, the face, the bend, and the throat. Of these, only the dimensions of the face and the throat section are determined by the design procedures of this manual. The size of the bend section is established by locating it a minimum distance upstream from the throat so that it will not control the flow.

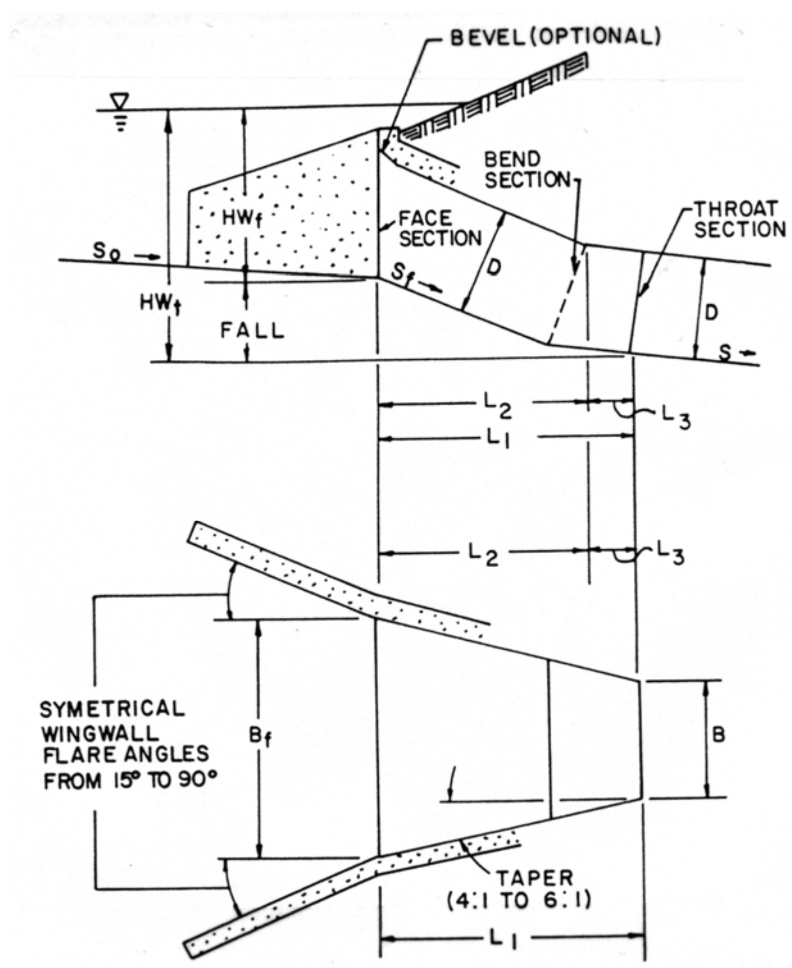


Figure 8.C.3 Slope-Tapered Inlet With Vertical Face

Appendix 8.C Tapered Inlets (continued)

8.C.3 Slope-tapered Inlet (continued)

The slope-tapered inlet combines an efficient throat section with additional head on the throat. The face section does not benefit from the FALL between the face and throat; therefore, the face sections of these inlets are larger than the face sections of equivalent depressed side-tapered inlets. The required face size can be reduced by the use of bevels or other favorable edge configurations. The vertical face slope-tapered inlet design is shown in Figure 8.C.3

The slope-tapered inlet is the most complex inlet improvement recommended in this manual. Construction difficulties are inherent, but the benefits in increased performance can be great. With proper design, a slope-tapered inlet passes more flow at a given headwater elevation than any other configuration. Slope-tapered inlets can be applied to both box culverts and circular pipe culverts. For the latter application, a square to round transition is normally used to connect the rectangular slope-tapered inlet to the circular pipe.

8.C.4 Hydraulic Design

Inlet Control

Tapered inlets have several possible control sections including the face, the bend (for slope-tapered inlets), and the throat. In addition, a depressed side-tapered inlet has a possible control section at the crest upstream of the depression. Each of these inlet control sections has an individual performance curve. The headwater depth for each control section is referenced to the invert of the section. One method of determining the overall inlet control performance curve is to calculate performance curves for each potential control section, and then select the segment of each curve which defines the minimum overall culvert performance. Figure 8.C.4

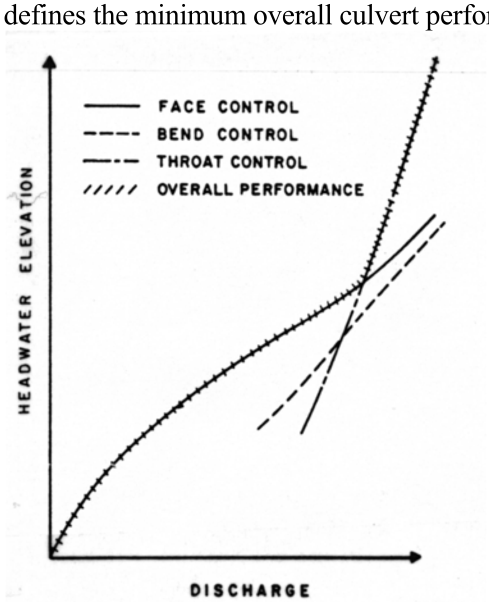


Figure 8.C.4 Inlet Control Performance Curve (Schematic)

Appendix 8.C Tapered Inlets (continued)

Inlet Control (continued)

Side-tapered Inlet

The side-tapered inlet throat should be designed to be the primary control section for the design range of flows and headwaters. Since the throat is only slightly lower than the face, it is likely that the face section will function as a weir or an orifice with downstream submergence within the design range. At lower flow rates and headwaters, the face will usually control the flow.

Slope-tapered Inlet

The slope-tapered inlet throat can be the primary control section with the face section submerged or unsubmerged. If the face is submerged, the face acts as an orifice with downstream submergence. If the face is unsubmerged, the face acts as a weir, with the flow plunging into the pool formed between the face and the throat. As previously noted, the bend section will not act as the control section if the dimensional criteria of this publication are followed. However, the bend will contribute to the inlet losses which are included in the inlet loss coefficient, K_E.

Outlet Control

When a culvert with a tapered inlet performs in outlet control, the hydraulics are the same as described in Section 8.5 for all culverts. The tapered inlet entrance loss coefficient (K_E) is 0.2 for both side-tapered and slope-tapered inlets. This loss coefficient includes contraction and expansion losses at the face, increased friction losses between the face and the throat, and the minor expansion and contraction losses at the throat.

8.C.5 Design Methods

Tapered inlet design begins with the selection of the culvert barrel size, shape, and material. These calculations are performed using the Culvert Design Form provided in Appendix B. The design nomographs contained in this Appendix are used to design the tapered inlet. The design procedure is similar to designing a culvert with other control sections (face and throat). The result will be one or more culvert designs, with and without tapered inlets, all of which meet the site design criteria. The designer must select the best design for the site under consideration.

In the design of tapered inlets, the goal is to maintain control at the efficient throat section in the design range of headwater and discharge. This is because the throat section has the same geometry as the barrel, and the barrel is the most costly part of the culvert. The inlet face is then sized large enough to pass the design flow without acting as a control section in the design discharge range. Some slight oversizing of the face is beneficial because the cost of constructing the tapered inlet is usually minor compared with the cost of the barrel.

Appendix 8.C Tapered Inlets (continued)

8.C.5 Design Methods (continued)

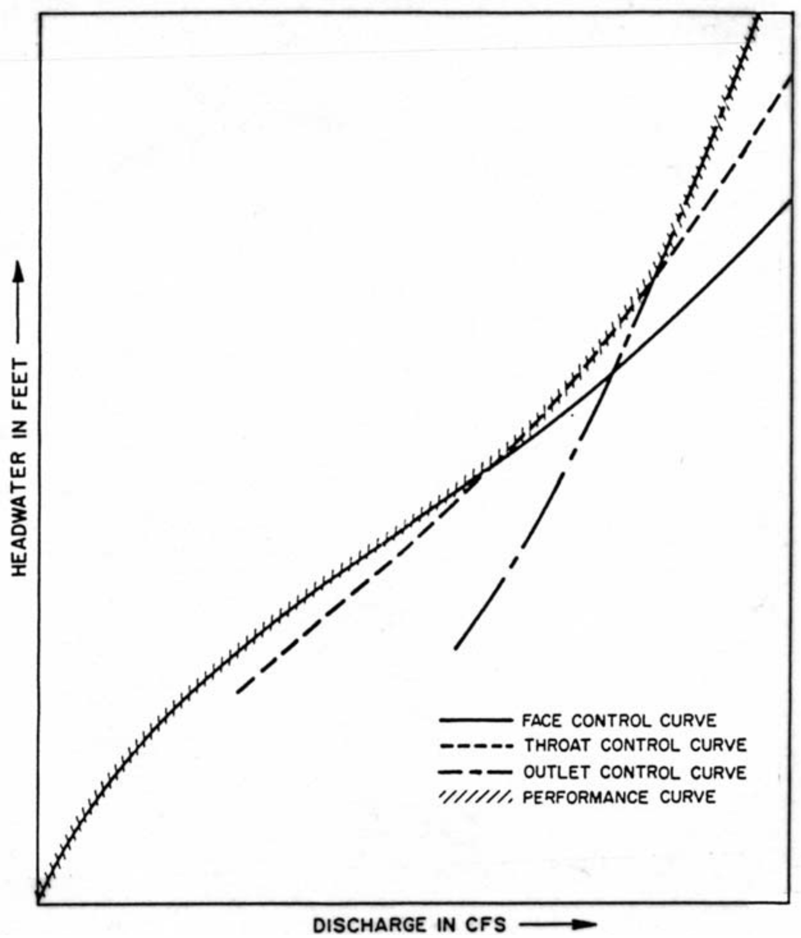
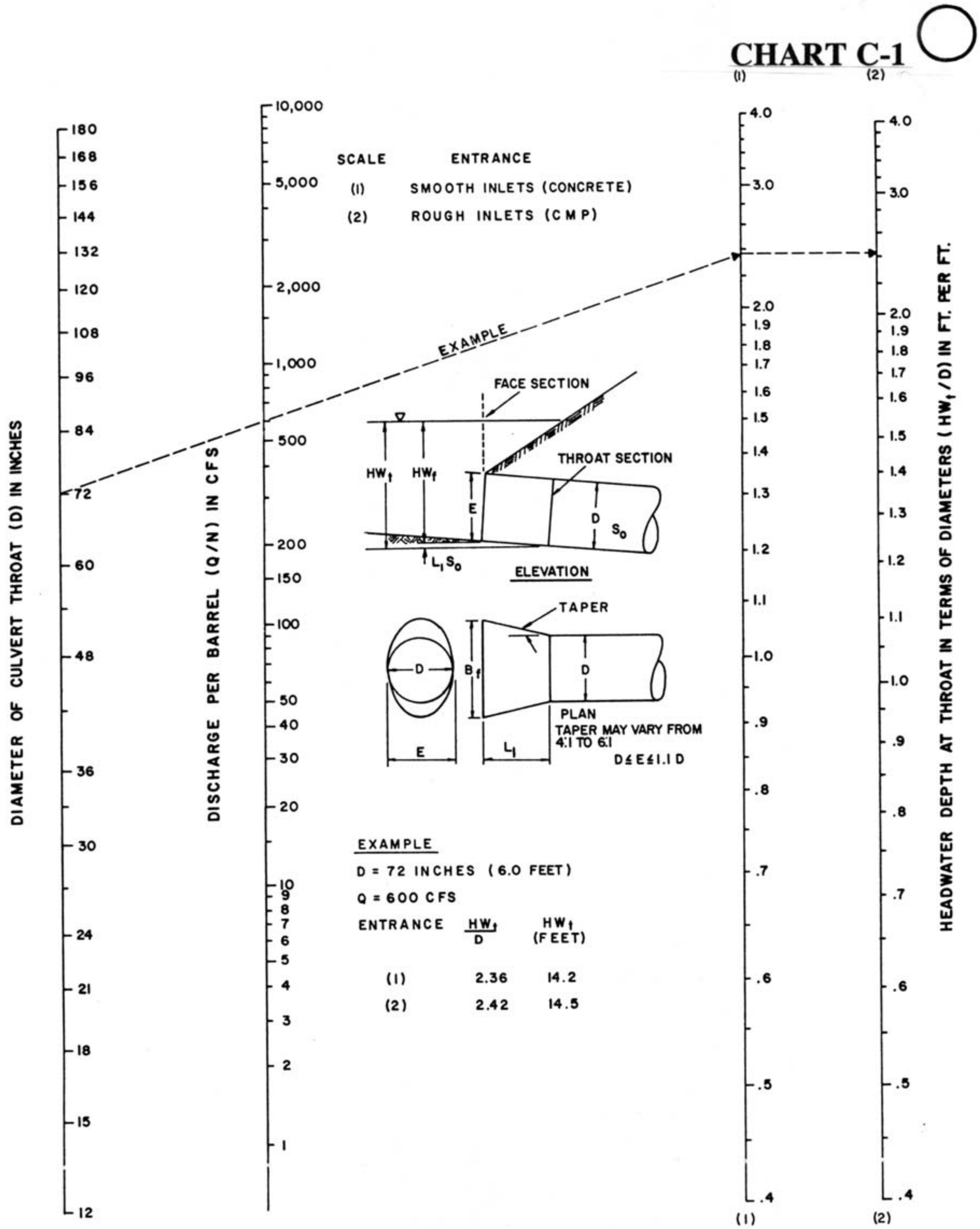


Figure 8.C.5- Culvert Performance Curve (Schematic)

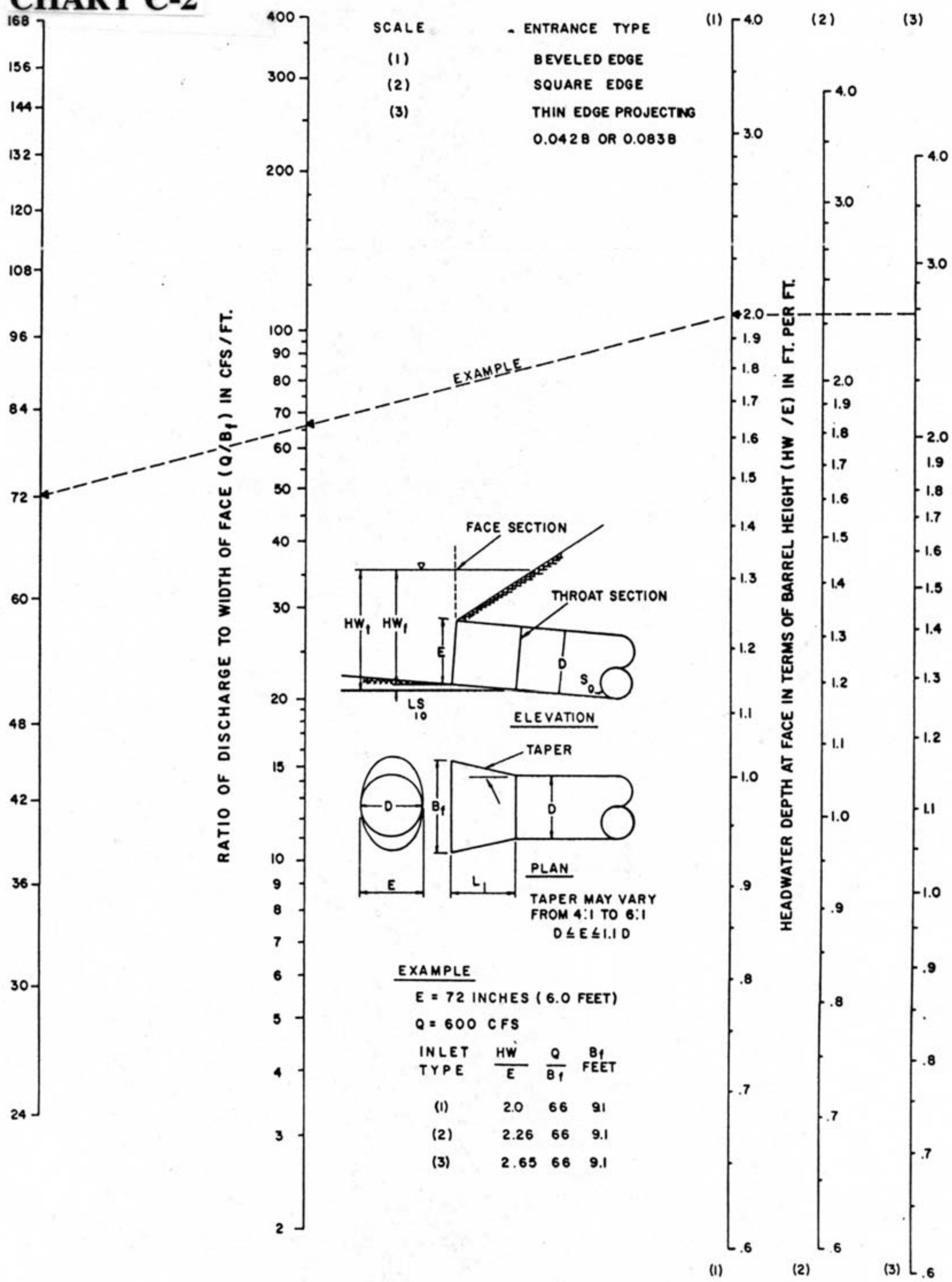
Performance Curves

Performance curves are of utmost importance in understanding the operation of a culvert with a tapered inlet. Each potential control section (face, throat, and outlet) has a performance curve, based on the assumption that particular section controls the flow. Calculating and plotting the various performance curves results in a graph similar to Figure 8.C.5, containing the face control, throat control and outlet control curves. The overall culvert performance curve is represented by the hatched line. In the range of lower discharges face control governs; in the intermediate range, throat control governs; and in the higher discharge range, outlet control governs. The crest and bend performance curves are not calculated since they do not govern in the design range.



THROAT CONTROL
FOR SIDE-TAPERED INLETS TO PIPE CULVERT
(CIRCULAR SECTION ONLY)

CHART C-2



EXAMPLE

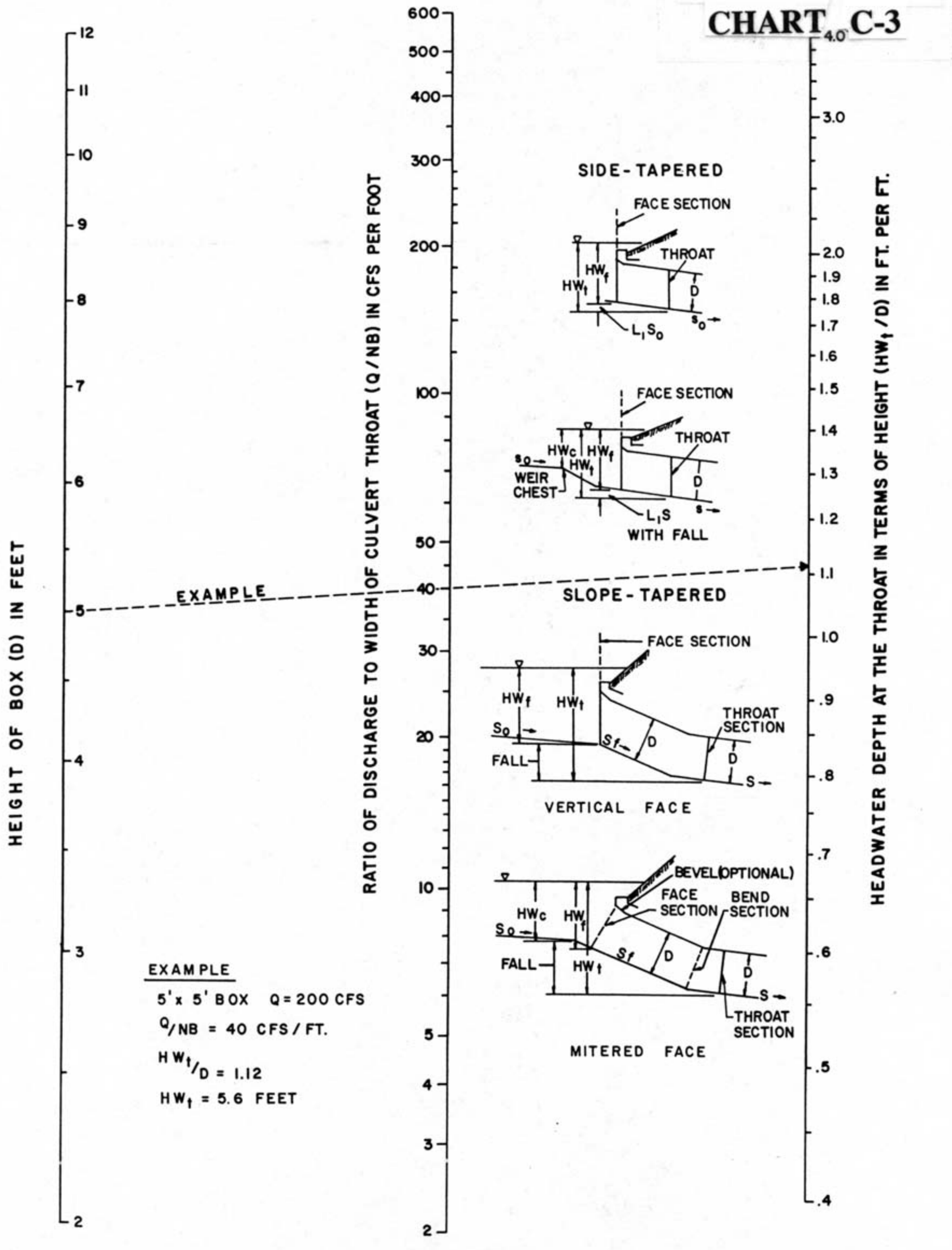
E = 72 INCHES (6.0 FEET)

Q = 600 CFS

INLET TYPE	$\frac{HW}{E}$	$\frac{Q}{B_f}$	B_f FEET
(1)	2.0	66	9.1
(2)	2.26	66	9.1
(3)	2.65	66	9.1

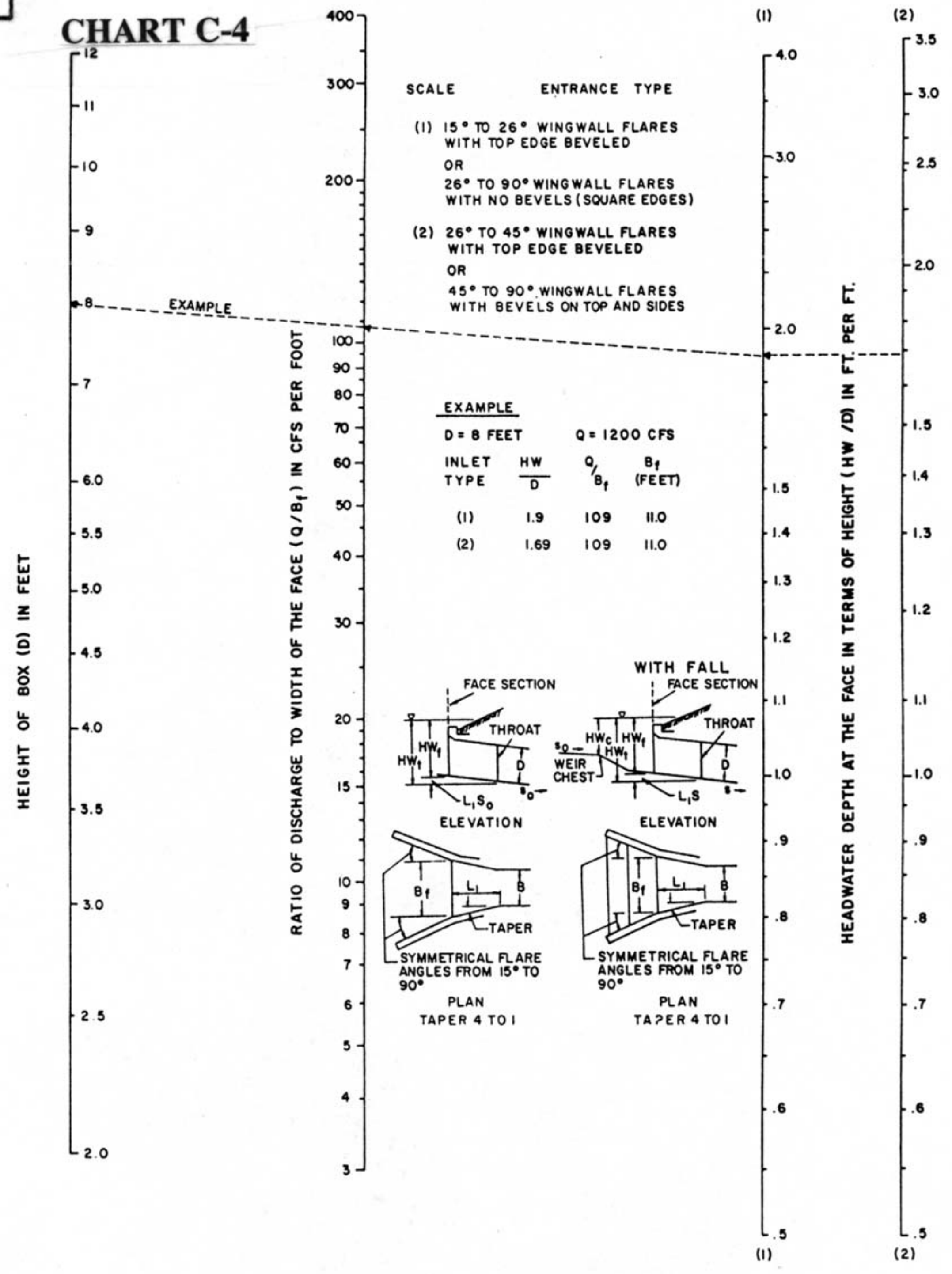
FACE CONTROL FOR SIDE-TAPERED INLETS TO PIPE CULVERTS
(NON-RECTANGULAR SECTIONS ONLY)

CHART C-3

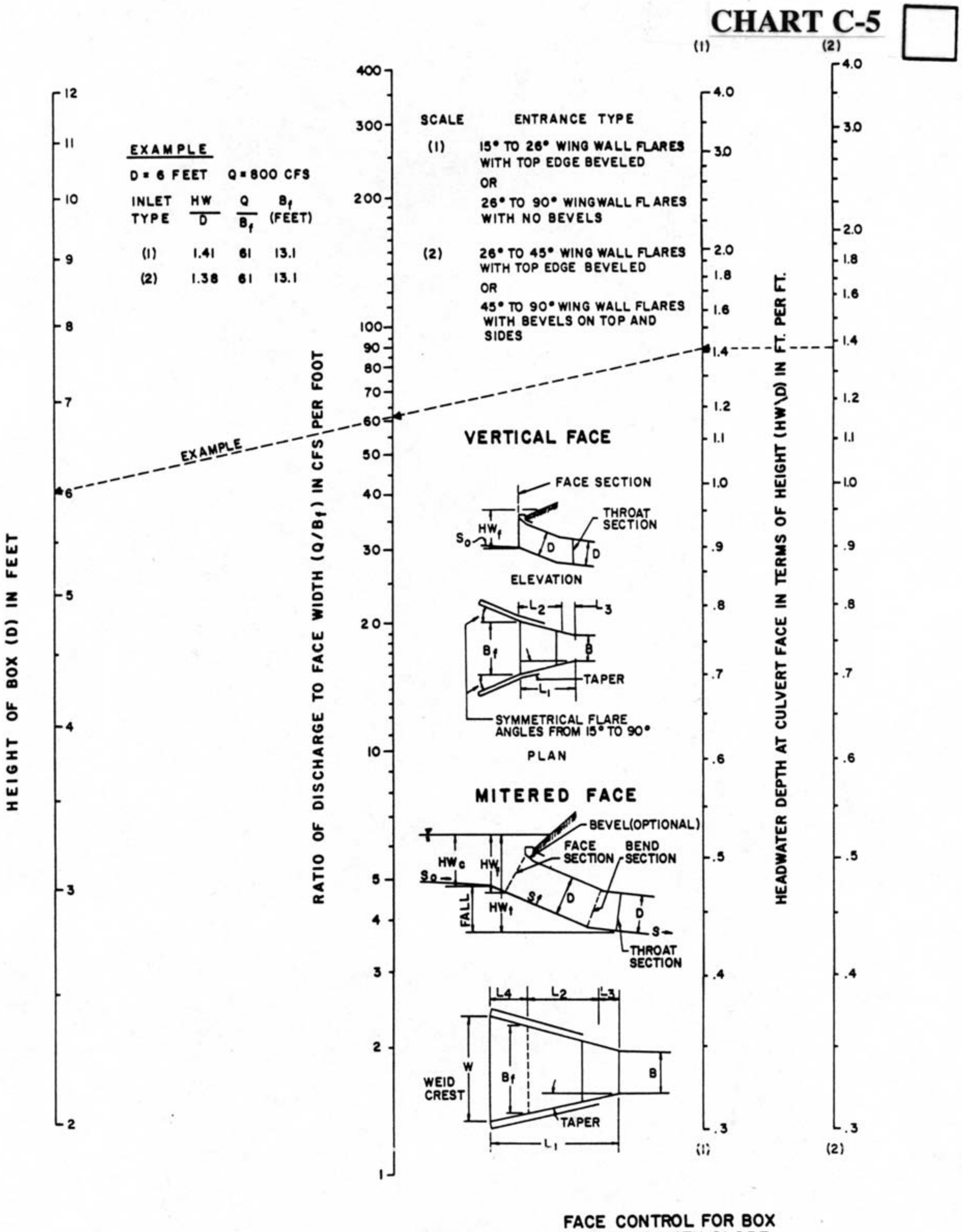


THROAT CONTROL FOR BOX CULVERTS WITH TAPERED INLETS

CHART C-4



FACE CONTROL FOR BOX CULVERTS WITH SIDE TAPERED INLETS



FACE CONTROL FOR BOX CULVERTS WITH SLOPE TAPERED INLETS

PROJECT: ______________________________
____

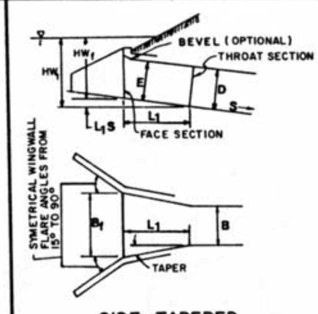
STATION: ______________________
SHEET ______ OF ______

TAPERED INLET DESIGN FORM

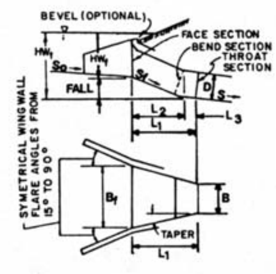
DESIGNER / DATE: ____________ / ________
REVIEWER / DATE: ____________ / ________

DESIGN DATA:

Q ____ = ______ cfs ; EL_{hi} __________ ft
EL. THROAT INVERT __________ ft
EL. STREAM BED AT FACE __________ ft
FALL ________ ft TAPER ________ : 1 (4:1 TO 6:1)
STREAM SLOPE, So = __________ ft/ft
SLOPE OF BARREL, S = __________ ft/ft
S_f ________ : 1 (2:1 TO 3:1)
BARREL SHAPE AND MATERIAL: ____________________
N = ________ , B = ________ , D = ________
INLET EDGE DESCRIPTION ____________________



SIDE-TAPERED



SLOPE-TAPERED

COMMENTS

Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f / E (3)	Q / B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE

(2) $HW_f = EL_{hi}$ - EL. FACE INVERT

(3) $1.1D \geq E \geq D$

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q/(Q/B_f)$

(6) MIN. $L_3 = 0.5NB$

(7) L_2 = (EL. FACE INVERT - EL. THROAT INVERT) S_f

(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_3$

(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_2$

(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER
SLOPE-TAPERED: $L_1 = L_2 + L_3$

(12) $HW_c = EL_{hi}$ - EL. CREST INVERT

(13) MIN. $W = 0.35Q / HW_c^{1.5}$

SELECTED DESIGN

B_f __________
L_1 __________
L_2 __________
L_3 __________
BEVELS ANGLE ____°
b = ____ in; d = ____ in
TAPER ________ : 1
S_f = ________ : 1

PROJECT: ______________________	STATION: ______________	MITERED INLET DESIGN FORM
______________________	SHEET ______ OF ______	DESIGNER / DATE: ________ / ______
		REVIEWER / DATE: ________ / ______

DESIGN DATA: N ______ ; B ______ ; D ______

Q ______ = ______ cfs ; EL_{hi} ______ ft

EL. THROAT INVERT ______ ft EL. STREAM BED AT CREST ______ ft

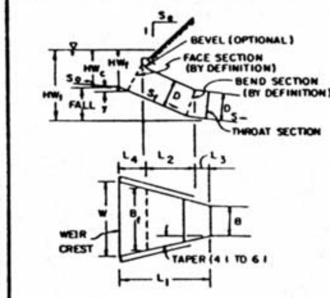
FALL ______ ft ; TAPER ______ : 1 (4:1 TO 6:1)

STREAM SLOPE, S_o ______ ft/ft ; BARREL SLOPE, S = ______ ft/ft

SLOPE OF THE EMBANKMENT S_e = ______ : 1 ; S_f ______ : 1 (2:1 TO 3:1)

BARREL SHAPE AND MATERIAL: ______________________

INLET EDGE DESCRIPTION: ______________________



SLOPE-TAPERED INLET/MITERED FACE

COMMENTS

Q (cfs)	EL_{hi}	EL. THROAT INVERT	y (1)	EL. FACE INVERT (2)	HW_f (3)	$\frac{HW_f}{E}$ (4)	$\frac{Q}{B_f}$ (5)	MIN. B_f (6)	SELECTED B_f	MIN. L_3 (7)	L_4 (8)	L_2 (9)	CHECK L_2 (10)	ADJ. L_3 (11)	ADJ. TAPER (12)	L_1 (13)	EL. CREST INV.	HW_c (14)	MIN. W (15)	W (16)

(1) $y = \left[\frac{(S_e \cdot S_f) - 1}{(S_e + S_f)(S_f^2 + 1)^{0.5}}\right] \cdot D$

(2) EL. FACE INVERT = EL. STREAM BED AT CREST - y

(3) $HW_f = EL_{hi}$ - EL. FACE INVERT

(4) $1.1D \geq E \geq D$

(5) FROM DESIGN CHARTS

(6) MIN. $B_f = Q/(Q/B_f)$

(7) MIN. $L_3 = 0.5\,NB$

(8) $L_4 = S_f y + D/S_f$

(9) L_2 = (EL. CREST INVERT - EL. THROAT INVERT) $S_f - L_4$

*** IF L_2 IS NEGATIVE DO NOT USE THIS INLET

(10) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right]$ TAPER $- L_3$

(11) IF (10)>(9), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$ TAPER $- L_2$

(12) IF (9)>(10), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B - NB}{2}\right]$

(13) $L_1 = L_2 + L_3 + L_4$

(14) $HW_c = EL_{hi}$ - EL. CREST INVERT

(15) MIN. $W = 0.35\,Q/(HW_c)^{1.5}$

(16) $W = NB + 2\left[\frac{L_1}{\text{TAPER}}\right]$

IF W<MIN. W, ADJUST TAPER

SELECTED DESIGN

B_f ______

L_1 ______

L_2 ______

L_3 ______

L_4 ______

BEVELS ANGLE ______ °

b = ______ in; d = ______ in

TAPER ______ : 1

S_f ______ : 1